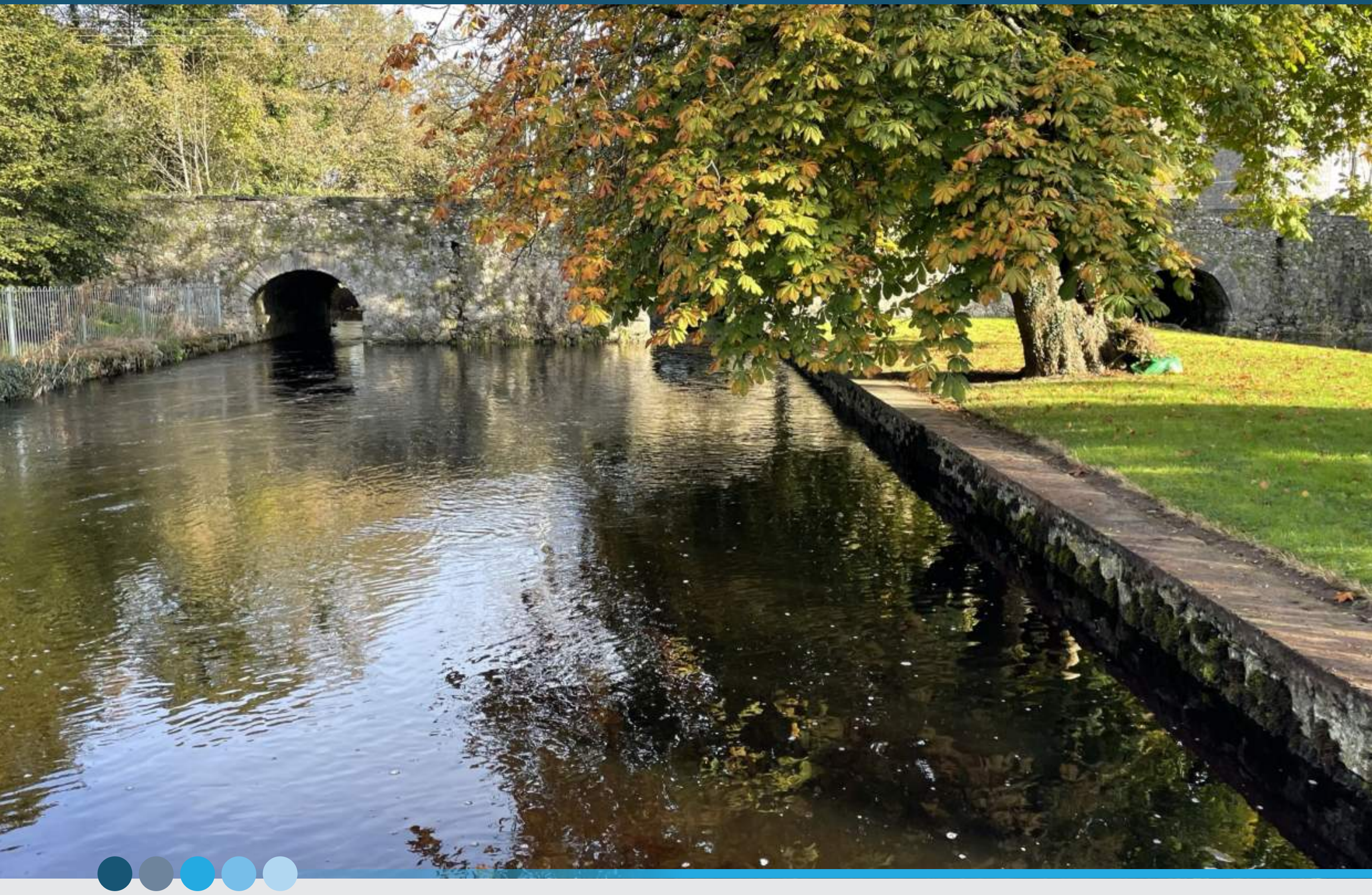
Ballinasloe Flood Relief Scheme
Hydrology Report

December 2021



Office of Public Works

Ballinasloe Flood Relief Scheme

Hydrology Report

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Abbreviations

AEP	Annual Exceedance Probability
AFA	Area of Further Assessment
ALLUV	Proportional extent of floodplain alluvial deposit
ALTBAR	Mean elevation of catchment (m)
AM	Annual Maximum
AREA	Catchment Area (km^2)
ARTDRAIN2	Fraction of Catchment that has undergone arterial drainage
BFISOIL	Soil baseflow index (estimate of BFI derived from soils, geology and climate data)
CFRAM	Catchment Flood Risk Assessment Management
C.I.	Confidence interval
CV	Coefficient of Variation
CWI	Catchment wetness index
Dij	Euclidean distance measure from the FSU
DRAIND	Drainage Density km/km^2
DTM	Digital Terrain Map
EDA	Exploratory data analysis
EPA	Environmental Protection Agency
ESB	Electricity Supply Board
EU	European Union
EV1	Extreme Value Type 1 = Gumbel (a 2-parameter distribution)
FAI	Flood attenuation index
FARL	Index of flood attenuation by reservoirs and lakes
FEH	Flood Estimation Handbook
FLATWET	PCD summarising proportion of time soils expected to be typically quite wet
FOREST	Proportional extent of forest cover FSE Factorial standard error
FRMP	Flood Risk Management Plan
FRS	Flood Relief Scheme
FSE	Factorial standard error
FSR	Flood Studies Report
FSSR	Flood Studies Supplementary Report
FSU	Flood Studies Update
GCC	Galway County Council
GEV	Generalised Extreme Value (a 3-parameter distribution)
GLO	Generalised Logistic (a 3-parameter distribution)
GSI	Geological Survey of Ireland
HA 26	Hydrological Area 26 (Upper Shannon)
HA 25	Hydrological Area 26 (Lower Shannon)
HEC	Hydrological Engineering Centre US Army Corp of Engineers
HEFS	High-End Future Scenario
HEP	Hydrological Estimation Point

HGF	Highest gauged flow
H-skew	Hazen-corrected skewness
iid	Independently and identically distributed
LA	Local Authority
L-CV	Coefficient of L-variation (Hosking and Wallis, 1997)
L-kurtosis	Coefficient of L-kurtosis (Hosking and Wallis, 1997)
L-skewness	Coefficient of L-skewness (Hosking and Wallis, 1997)
LN2	2-parameter lognormal (a distribution)
LN3	3-parameter lognormal (a distribution)
LO	Logistic (a 2-parameter distribution)
LP3	Log Pearson Type 3
Malin	OS Malin Head Datum (Mean Sea level)
mOD	Metres above Ordanance Datum (Malin)
MRFS	Mid-Range Future Scenario
MSL	Mainstream length (km)
NERC (UK)	Natural Environment Research Council
NETLEN	Total length of river network above gauge (km)
NWRM	Natural Water Retention Measure
OSi	Ordnance Survey Ireland
OPW	Office of Public Works
PASTURE	Proportional extent of catchment area classed as grassland/pasture/agriculture
PDF	Probability density function
PEAT	Proportional extent of catchment area classified as peat bog
PCD	Physical Catchment Descriptor
Poolbeg	OSi Poolbeg Datum (Lowest Astronomical Tide at Poolbeg Lighthouse)
POT	Peaks Over Threshold
QBAR	Mean annual maximum flood flow
QMED	Median annual maximum flood flow
Q_T	T-year flood
ROI	Region of influence
S1085	Slope of the main stream excluding the bottom 10% and top 15% of its length (m/km)
SAAPE	Standard-period average annual potential evapotranspiration (mm)
SAAR	Seasonal Annual Average Rainfall
SE, se	Statistical standard error (of an estimate)
SOIL	FSR Soil index based on WRAP classifications
SPR	Standard Percentage Runoff
Tb	Time of Base
Tp	Time to peak
Tc	Time of Concentration
TUH	FSR Triangular Unit Hydrograph
URBANEXT	Urban Fraction of Catchment

UAF	Urban adjustment factor
UoM	Unit of Management
WI	Waterways Ireland
WRAP	FSR Winter Rainfall Acceptance Potential - soil class

1 Introduction

1.1 Background

The Office of Public Works (OPW), in partnership with Galway County Council (GCC) and other Local Authorities, have completed a Catchment Flood Risk Assessment and Management Study (CFRAMS) for the Shannon Catchment, which includes the catchment of the River Suck. The Catchment Flood Risk Management Plan (CFRMP), which was published in 2018, concluded that a flood relief scheme for Ballinasloe would be viable and effective.

Arising from the CFRMP, OPW has now commissioned Arup and Hydro Environmental Ltd. to develop a flood relief scheme for Ballinasloe. The project consists of five stages as follows:

- Stage I: Identification and Development of a Preferred Scheme
- Stage II: Public Exhibition/ Planning Process
- Stage III: Detailed Construction Design, Compilation of Work Packages and the Preparation of Tenders for Contracts and Confirmation Documents
- Stage IV: Construction Supervision & Project Management Services
- Stage V: Handover of Works

This Hydrology Report is produced as part of Stage I of the project.

This hydrological analysis considers the flood risk emanating from the River Suck, its local tributaries and drainage areas on the town of Ballinasloe and establishes best estimates of return period flood flow magnitudes and hydrographs within the Ballinasloe Flood Relief Scheme Area. These flood flow and hydrograph estimates are required as inputs to the hydraulic flood model of the river network and floodplain areas within the Ballinasloe FRS area. The flood relief scheme area is presented below in Figure 1-1.

1.2 General Hydrological Description

The main river flowing through Ballinasloe is the River Suck which joins the River Shannon a short distance downstream of Shannon Bridge. The River Suck has a hydrometric gauging station located 4km upstream of Ballinasloe at Bellagill (Gauge Reference 26007). This gauge is in operation since 1952 and has 68years of annual maximum flood flows currently available. The catchment area of the Suck to this gauge is estimated to be 1,207km^2 and the catchment area to downstream of the Marina at Ballinasloe Town is 1,428km^2, representing an increase of 20%.

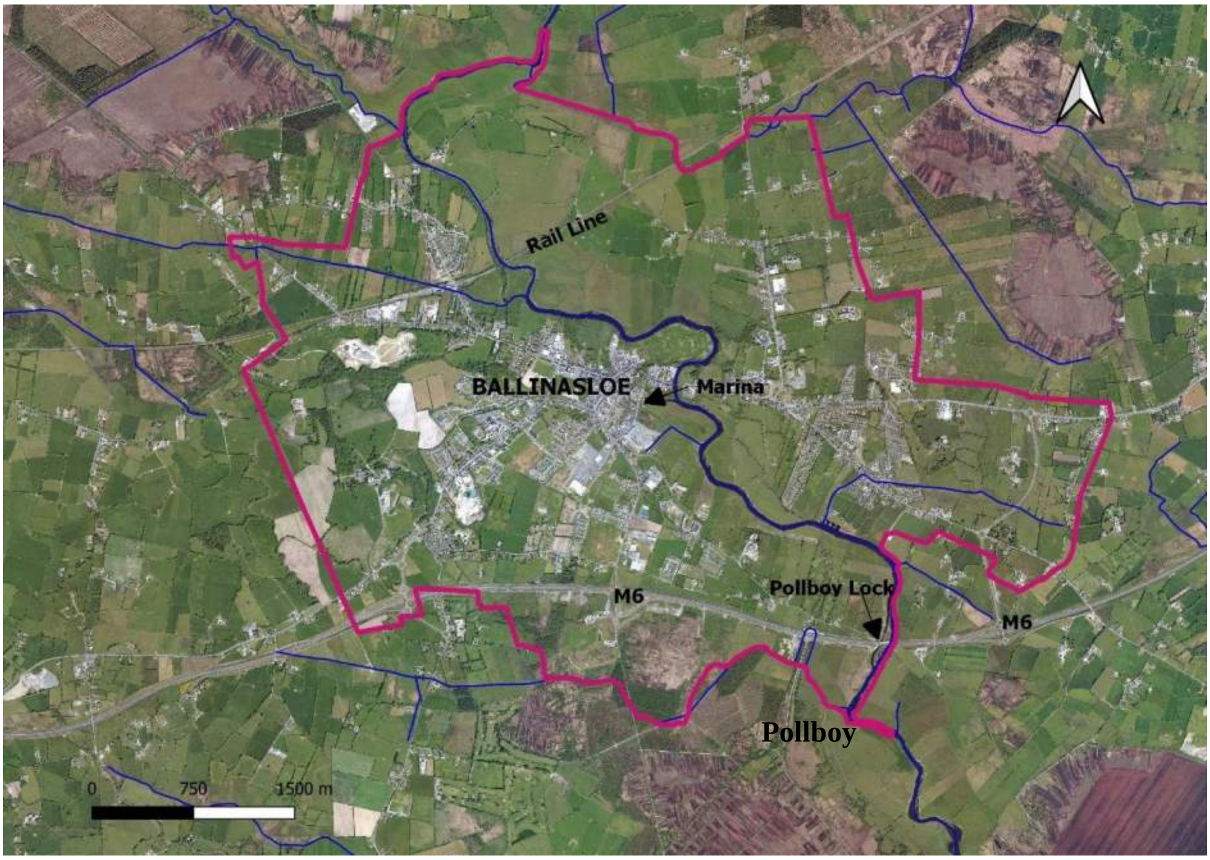

Figure 1-1 Ballinasloe Flood Relief Scheme Area

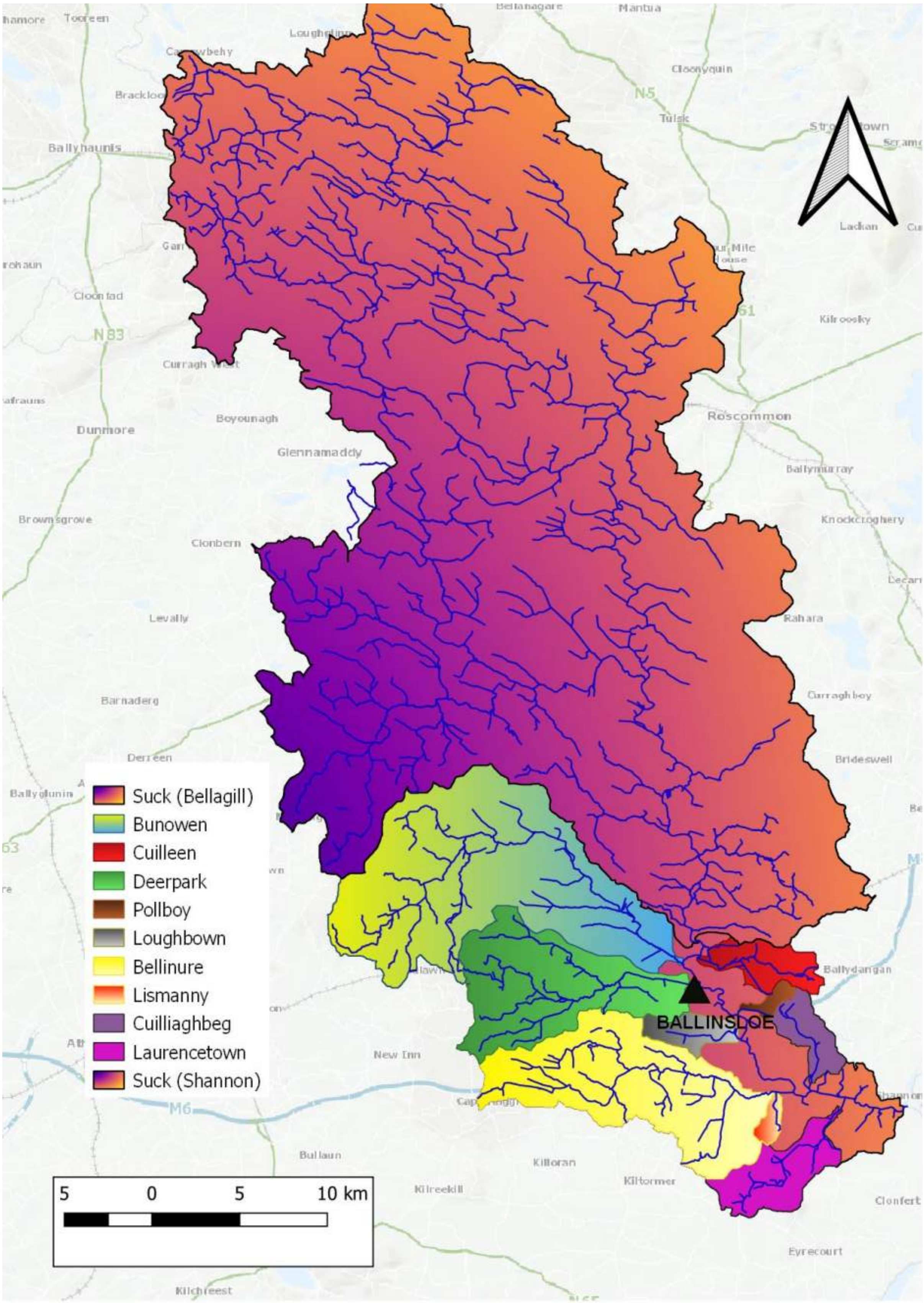

Figure 1-2 River Suck Catchment Map

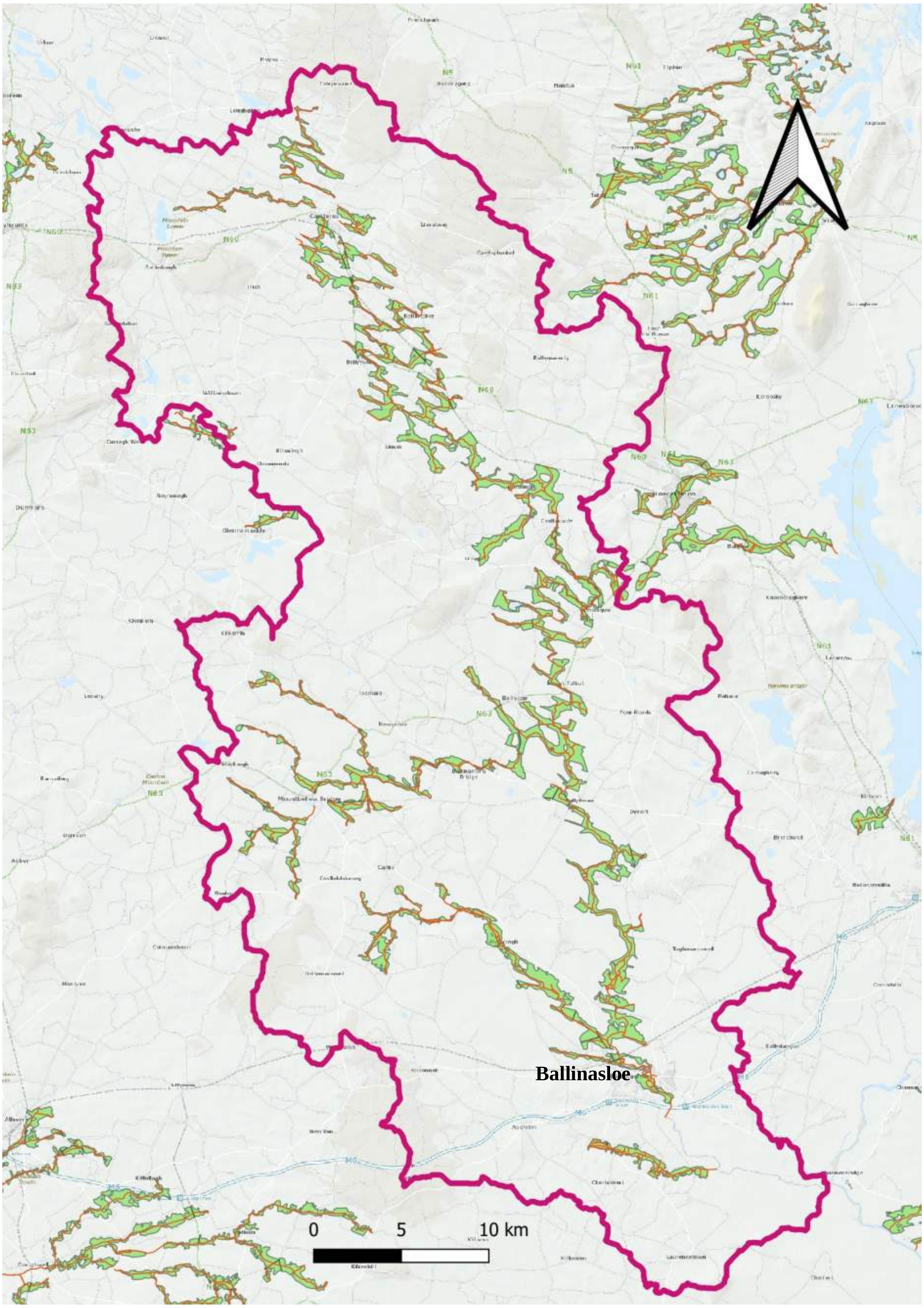

Figure 1-3 Drainage District Benefitting Lands Mapping within River Suck Catchment

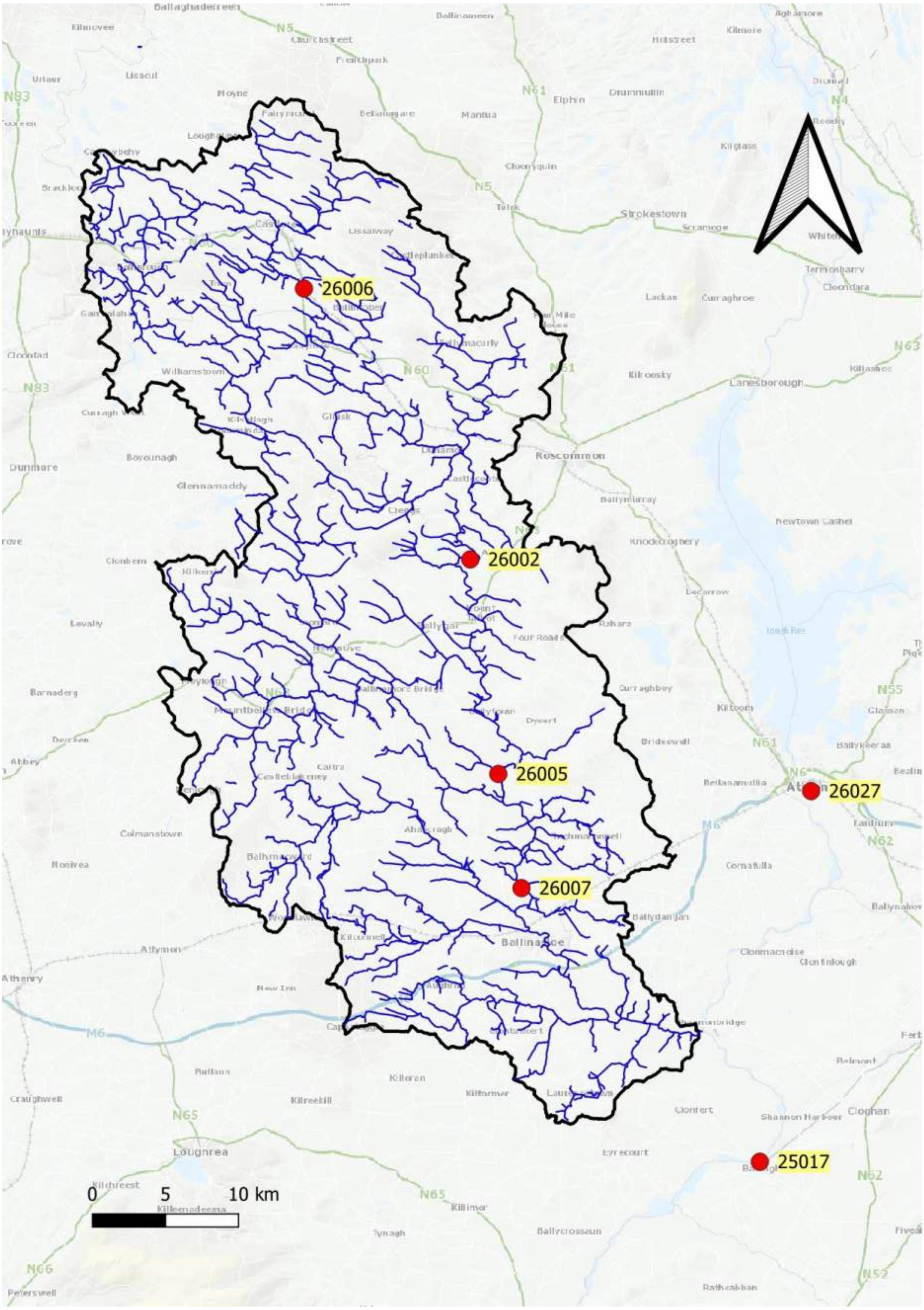

Figure 1-4 Primary Relevant Hydrometric Flows Gauging Stations

The main tributaries entering below Bellagill gauging station from upstream to downstream are Cuilleen Stream (13.5km^2), Bunowen River (137km^2), Deerpark River (62km^2), Loughbown Stream (8.5km^2), Pollboy Stream, and further downstream of the study area is the Ballinure (Cloonescragh) River (79km^2), refer to Figure 1-2. All of these tributaries are ungauged. The River Suck is also gauged upstream at Derrycahill (26005), catchment area 1085.4 km^2, since 1954 (providing a 66 year record) and at two gauges further upstream, namely Rockwood(26002) and Willsbrook (26006), refer to Figure 1-4. There are a number of other hydrometric stations that only provide continuous river levels as reliable rating relationships have not been developed, refer to Figure 1-5.

There are a number of water level recorder stations on the River Suck and tributaries that will be utilised in this study both in respect to the shape of the flood hydrograph and timing of the flood peak but also for calibration and verification of the hydraulic flood model in respect to predicted flood levels within the model reach. On the River Suck, stations 26354 was installed as part of the Ballinasloe flood relief scheme and a number of flow ratings measurements (7 in total) have been carried out to date (ranging from 13.1 to 74.7cumec). Station 26355 records water level on the old River Suck channel in the Townparks area. A further three stations for recording water level have recently been installed by the OPW as part of this study and these are 26402 and 26357 on the Deerpark at Ballinasloe Rail Station and Deerpark Bridge and station 26358 on the Bunowen River at Bunowen Bridge, refer to Figure 1-5.

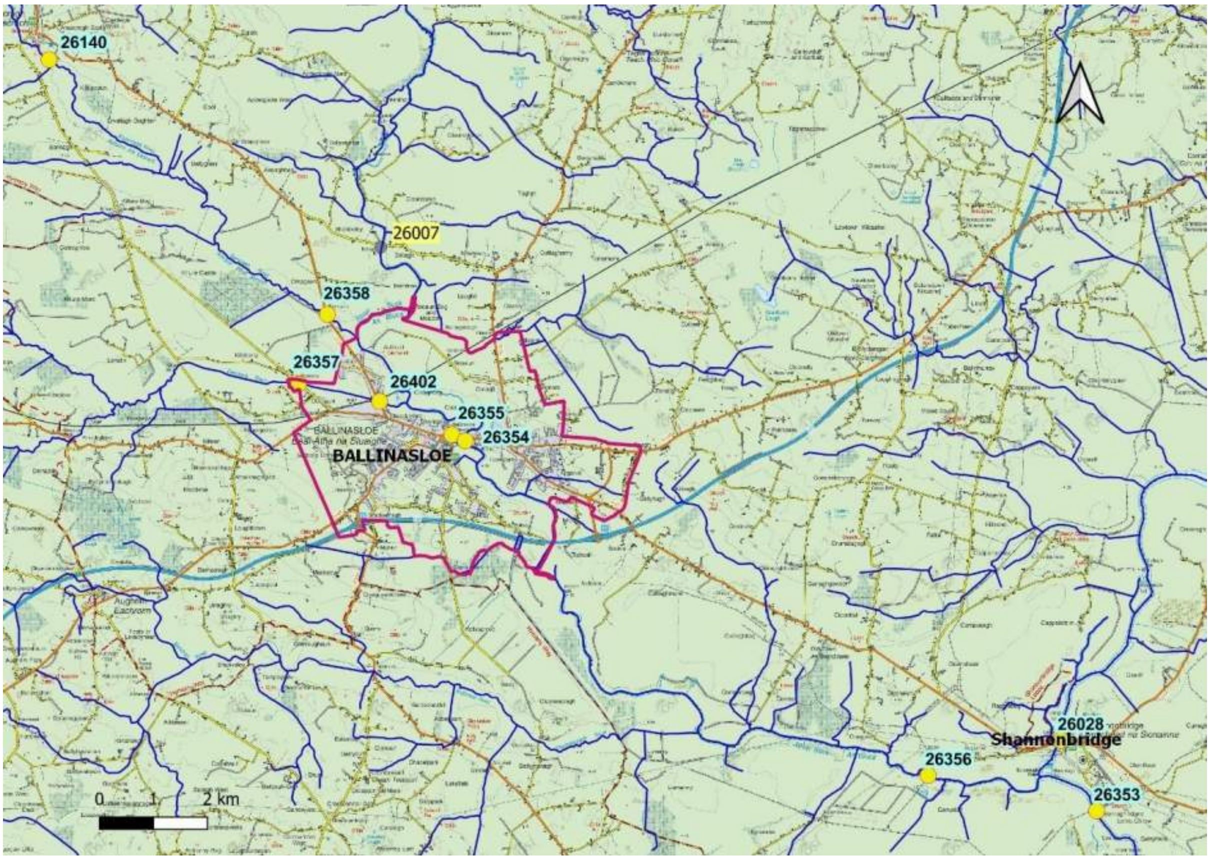

Figure 1-5 Relevant Hydrometric Water Level Gauging Stations within Study Area

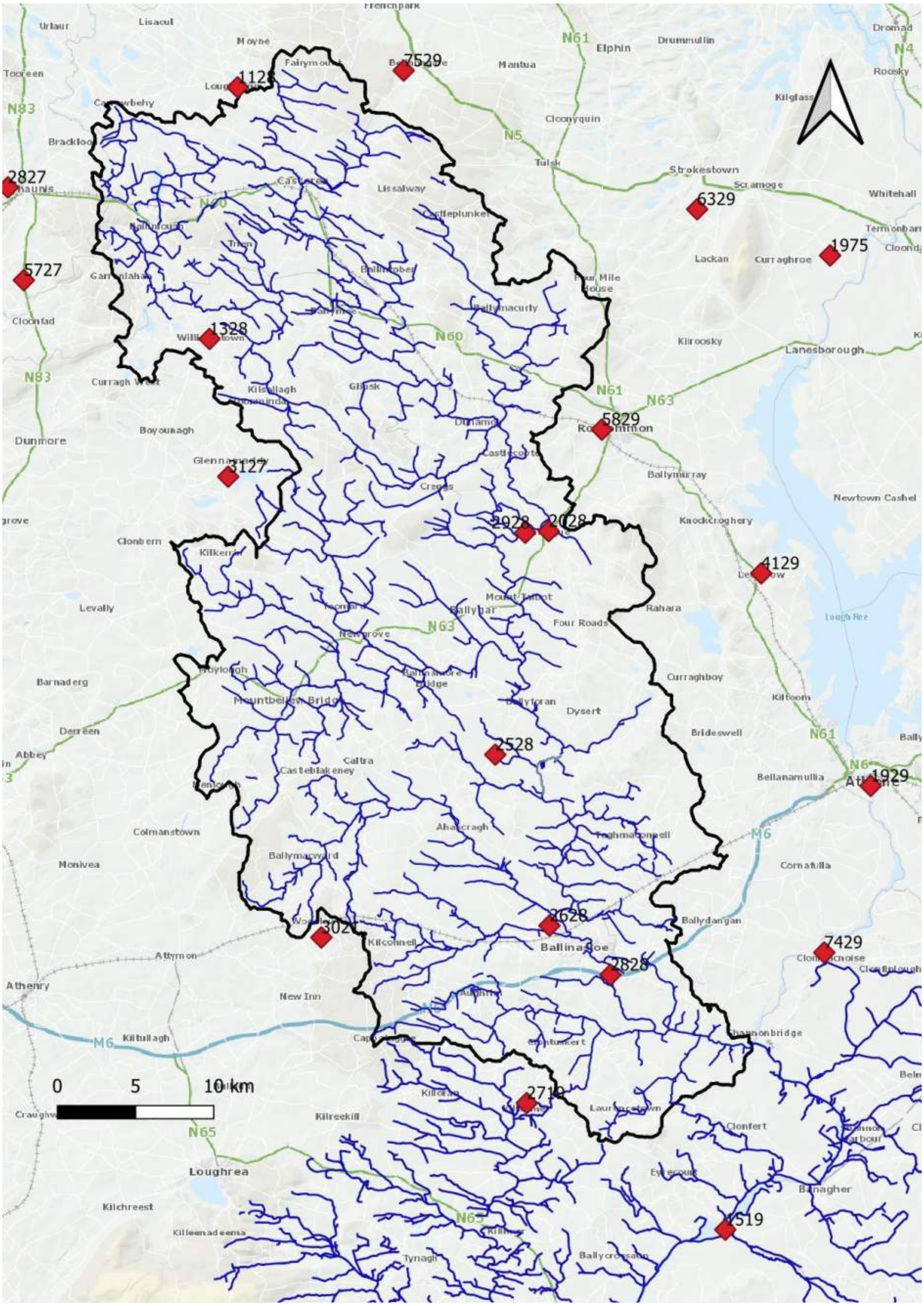

Figure 1-6 Relevant Daily Read Rainfall Gauges for the Suck Catchment

2 Data Collection

2.1 Introduction

Various datasets relevant to catchment hydrology of the Suck and Shannon have been collated for inclusion in the hydrological assessment of catchment flood flows within the Study Area. These datasets are summarised as follows:

<u>EPA</u>
EPA hydrometric data sets
EPA river network mapping (OSi Geometric River Network)
Corine Land-use mapping (2018)

<u>EU</u>
Copernicus EMS mapping (relevant to flood inundation associated with 2015/2016 flood event).

<u>Geological Survey of Ireland (GSI)</u>
Soils and subsoil mapping
Bedrock mapping
Groundwater recharge mapping
Aquifer mapping
Aquifer vulnerability mapping
Karst features mapping

<u>Local Authority – Galway County Council (GCC)</u>
Historical flood information
Storm drainage catchments and storm, foul and combined sewer network details
Planning and development information in respect to current and urban footprint

<u>Met Eireann</u>
Gauged rainfall data from Synoptic Stations and daily rainfall gauging stations for the Upper Shannon – Hydrometric Area 26 (total of 28 rainfall stations relevant to the catchment area)
Seasonal Average Annual Rainfall (SAAR) – 2km grid model
Storm Rain Depth Duration Frequency model – 2km grid dataset
Merá – Meteorological datasets (1981 – 2015) – Total precipitation on 2.5km grid

<u>OPW</u>
OPW hydrometric data at relevant gauges described later refer in Section 3 for list of gauging stations
OPW FSU Physical Catchment Descriptor data set
OPW gauged hydrometric catchment boundaries
OPW CFRAM river survey cross-section data
OPW CFRAM reports for the Upper Shannon and Ballinasloe AFAs
OPW Digital Terrain Mapping (DTM)
OPW historical flood data

<u>OSI</u>
Vector mapping datasets
Historical OSI mapping

Orthographic mapping
OSi PRIME-2 dataset

Waterways Ireland
Hydrometric data
Survey data

2.2 Review of Physical Catchment Descriptor datasets

The OPW Flood Study Update (FSU, OPW web portal) physical catchment descriptors data set for gauged and ungauged river nodal points have been provided along with catchment and sub-catchment boundaries and the OSI river channel network. This data was reviewed for any discrepancies which may be present due to mapping error or due to catchment land-use changes or temporal changes in a data set, such as changes in the long term annual rainfall. Catchment boundaries were checked against DTM and the OSI drainage network for inconsistencies. Particular attention was paid to the catchment areas in respect to the watershed divide and the channel network and the resultant catchment area. The PCDs were checked for consistency within the hydrological estimation area between upstream and downstream HEPs. It was found that no significant changes in the FSU PCD's were warranted for the Scheme Area HEPs with only very slight adjustments required for consistency of the following parameters AREA, S1085, MSL and URBEXT.

A sample selection of the PCD's at Ballinasloe for the larger watercourses, namely the River Suck, the Bunowen River, and the Deerpark River are presented in following Tables Table 2-1 to Table 2-3. The PCD dataset review found that the PCDs established in the FSU are generally representative and no significant errors were identified. The relevant PCD's that were considered are those PCD's that are directly or indirectly associated with the parameter input to the FSU flood estimation equation described in Section 5.5.

The Suck Catchment to Ballinasloe has a catchment area of 1428km^2; its catchment characteristics are summarised below in Table 2-1. These are taken at the Ballinasloe Marina downstream of the Townparks in the centre of Ballinasloe. The River Suck joins the River Shannon c. 15km downstream of Ballinasloe and 800m downstream of Shannonbridge, having a total catchment area of 1599km^2.

The PCDs show the River Suck catchment to be a rural catchment with a very minor urban fraction of 0.34%. The catchment has negligible OPW arterial drainage extents. However, there is a considerable extent of drainage district areas within the upstream catchment under the control of Galway Co. Council and which may be subject to varying degrees of channel maintenance, refer to Figure 1-3. Local Authority Drainage District channel are generally considerably less maintained than the OPW Arterial Drainage scheme channels. Such drainage districts and benefitting lands are not included for in the FSU equation under the ARTDRAIN factor and are not included for in this study as the frequency of maintenance is relatively low with small local sections of maintenance carried out depending on priority and limited budget. The soil baseflow index represents a moderate to low catchment flood runoff index. The land-use is predominantly agriculture at 71%, followed by peatland at 19.3% and Forestry at only 8.2%. The FARL index is low due to the limited extent of lakes within the catchment. This index does not however reflect the naturally significant attenuation within the Suck floodplain area both upstream and particularly downstream of Ballinasloe. The main channel slope is moderate to low at an average fall of 1 in 2500 and the main channel longitudinal length of 115km.

Table 2-1 Suck Catchment FSU Physical Catchment Descriptors to Ballinasloe Marina

FSU PCD	Magnitude	Description
AREA (km^2)	1428	Catchment area as delineated from the DTM model
ALTBAR m OD	75.8	Average catchment altitude
SAAR	1048	Long term standard average annual Rainfall
FARL	0.985	Index of flood attenuation by Reservoirs and lakes
URBEXT (%)	0.34	The proportional extent of catchment area mapped as urbanised
FOREST (%)	8.18	The proportional extent of forestry
PEAT(%)	19.33	The proportional extent of catchment area classified as peat bog
PASTURE(%)	70.77	The proportional extent of catchment area classified as grassland/pasture/agriculture
ALLUV(%)	2.46	The proportional extent of floodplain alluvial deposits
BFISOIL	0.596	Catchment soil baseflow index
DRAIND (km/km2)	0.764	Drainage density
S1085 (m/km)	0.3948	The slope of the main stream between the bottom 10% and top 15% of the catchment main stream length
ARTDRAIN (%)	0.02	The proportion of catchment area mapped as benefitting from arterial drainage schemes (including drainage districts)
MSL (km)	114.7	The main stream length of the river

These PCDs suggest a time to peak for the Suck to Ballinasloe of c. 27hours based on the Flood Studies Supplementary Report design Storm unit hydrograph method (NERC, 1985). The expected critical storm duration is 54hours. In the hydrograph analysis presented in Section 9 the antecedent rainfall and long lead-in rainfall period required to produce flood events increased significantly the critical duration for flooding in the River Suck at Ballinasloe.

The PCDs for the main tributary inflow at Ballinasloe from the Bunowen and Deerpark Rivers are presented below in Table 2-2 and Table 2-3, respectively.

Table 2-2 Bunowen catchment FSU physical catchment descriptors to River Suck confluence upstream of Ballinasloe

FSU PCD	Magnitude	Description
AREA (km^2)	136.7	Catchment area as delineated from the DTM model
ALTBAR m OD	72.5	Average catchment altitude
SAAR	1080	Long term standard average annual Rainfall
FARL	0.999	Index of flood attenuation by Reservoirs and lakes
URBEXT (%)	0.42	The proportional extent of catchment area mapped as urbanised
FOREST (%)	7.9	The proportional extent of forestry
PEAT(%)	10.4	The proportional extent of catchment area classified as peat bog
PASTURE(%)	79.2	The proportional extent of catchment area classified as grassland/pasture/agriculture
ALLUV(%)	0.9	The proportional extent of floodplain alluvial deposits
BFISOIL	0.628	Catchment soil baseflow index
DRAIND (km/km2)	0.736	Drainage density
S1085 (m/km)	2.023	The slope of the main stream between the bottom 10% and top 15% of the catchment main stream length
ARTDRAIN (%)	0.00	The proportion of catchment area mapped as benefitting from arterial drainage schemes (including drainage districts)
MSL (km)	32.5	The main stream length of the river

Table 2-3 Deerpark catchment FSU physical catchment descriptors to River Suck confluence downstream of Ballinasloe Rail Bridge

FSU PCD	Magnitude	Description
AREA (km^2)	61.6	Catchment area as delineated from the DTM model
ALTBAR m OD	74	Average catchment altitude
SAAR	1064	Long term standard average annual Rainfall
FARL	0.994	Index of flood attenuation by Reservoirs and lakes
URBEXT (%)	1.55	The proportional extent of catchment area mapped as urbanised
FOREST (%)	6.55	The proportional extent of forestry
PEAT(%)	5.32	The proportional extent of catchment area classified as peat bog
PASTURE(%)	87.34	The proportional extent of catchment area classified as grassland/pasture/agriculture
ALLUV(%)	1.62	The proportional extent of floodplain alluvial deposits
BFISOIL	0.642	Catchment soil baseflow index
DRAIND (km/km^2)	0.941	Drainage density
S1085 (m/km)	2.777	The slope of the main stream between the bottom 10% and top 15% of the catchment main stream length
ARTDRAIN (%)	0.0	The proportion of catchment area mapped as benefitting from arterial drainage schemes (including drainage districts)
MSL (km)	17.4	The main stream length of the river

These tributary catchments are relatively similar to the Suck catchment in terms of land use and flood runoff rates. They are slightly steeper and smaller in extent with much shorter main stream lengths and, therefore, during a flood event they are likely to react faster to rainfall and peak earlier than the Suck with estimated time to peaks of c. 9hours.

Within the scheme area there are a number of very small sub-catchment areas, nineteen areas in total draining to the Suck which are included for in the catchment area specified at the various HEPs along the River Suck mainline reach. The hydraulics report considers some of these minor drainage areas directly within the 2-D model domain. The drainage areas that may contribute to inflow behind potential defended areas will be identified and presented in the hydraulics assessment.
The PCD's from at all of identified HEPs on the Rivers and smaller tributaries have been reviewed and updated for this study with minimal changes required from the original CFRAM and FSU PCD data.

2.3 CFRAM review

The Shannon Catchment Flood Risk Assessment and Management (CFRAM) Study was one of seven River Basin District studies carried out across the Republic of Ireland from 2011 to 2016 the requirements of the EU Floods Directive (Directive 2007/60/EC) and the 2004 Flood Policy Review Report. The Ballinasloe area was included in the CFRAM assessment under Unit of Management (UoM) 25/26 (Shannon Upper and Lower, Hydrometric Areas 25 and 26). The CFRAM study included detailed hydrological and hydraulic modelling assessments to quantify the flood risk from fluvial and coastal sources and to identify management measures to protect vulnerable receptors.

The flood estimation approach adopted in the CFRAM study of the Ballinasloe AFA is the FSU PCD flood estimation method with pivotal site and pooling group derived from hydrologically similar gauging stations and the IH124 flood estimation equation for the smaller catchments < 25km^2 in area. A similar approach has been adopted in this study but using the more up to date AM flood flow series from the various pooling sites and consideration of a pooled growth curve both geographically and hydrologically similar, refer to Section 5.

2.3.1 Design Flood Magnitudes

The CFRAM hydrology report gives the following recommended growth factors for the Suck and the Bunowen and Deerpark rivers.

Table 2-4 CFRAM Flood Growth Factors for Suck and main tributaries at Ballinasloe

River	Return Period Flood Growth Factor $X_T = Q_T/QMED$		
	10yr	100yr	1000yr
Suck	1.37	2.06	3.23
Bunowen	1.34	1.77	2.18
Deerpark	1.43	1.96	2.49

There is limited information in the CFRAM hydrology Report as to the actual modelled design flow magnitudes at the various reaches and HEPs. Flood flow magnitudes were extracted from the CFRAM Flood Extent mapping for the Ballinasloe area and are summarised below in Table 2-5.

Table 2-5 CFRAM Return Period Flood Flows for Suck and main tributaries at Ballinasloe

River	Location	Peak Return Period Flood Flow Q_T (cumec)		
		10yr	100yr	1000yr
Suck	Bellagill	122	182	273
Suck	Pollboy area	160	236	368
Bunowen	Upstream of Suck confluence	23.9	31.4	35.8
Deerpark	Upstream of Suck confluence	15.2	20.8	26.4

2.4 Review of Groundwater Flooding

The Ballinasloe study area is underlain by a regionally important karstified (conduit flow) limestone bedrock aquifer. The bedrock formation is Dinantian pure bedded limestone and the groundwater body within the much of the Scheme area is the Suck South Groundwater Body. The quaternary overburden is primarily peat and alluvial deposits located along the relatively flat low-lying floodplain area of the Suck and lower reaches of the Shannon.

Information on the underlying bedrock formation and underlying aquifers was obtained from the GSI groundwater mapping database. The assessment also examined the GSI Karst Database of Features, and reviewed the historical 25inch mapping which identifies historical springs and liable to flood areas. The GSI Groundwater flood maps were also examined which identified karst flooding extents associated with turlough features. No such flooding features were identified within the Ballinasloe scheme area from this mapping. The karst database showed no identified karst features within the scheme area. The nearest significant karst features, namely turloughs with swallow-hole drainage features are located at Cranberry Lough 4km to the ENE of the scheme and the large Carrownure, Glannanea, Turlaghmore, Onagh, Carrowduff and Garbally and between 6 to 8km NE of the scheme in the Taghmaconnell area. Tracer studies carried out by the GSI identified that the karst flow direction was northwest away from the scheme area between turloughs and their swallow-holes and a large spring which forms the Killeglan Public supply at Rockland which eventually drains west as the Killeglan stream to the River Suck confluence, 6km upstream of Belagill. There is a clear absence of karst features within and surrounding Ballinasloe Scheme area suggesting little surface karst features and turlough areas.

The GSI bedrock mapping presented in Figure 2-1 shows the upper two-thirds of the scheme area to be underlain by the Marine Shelf Facies Formation which is a Visean age, undifferentiated limestone and is classified by the GSI as a regionally important karstified (conduit flow) limestone bedrock aquifer. In the southern section of the scheme area the underlying Limestone is the Tobercolleen and Lucan Formation also known as calp limestone formation, which is a dark grey argillaceous and cherty Limestone and Shale which is classed by the GSI as a locally Important (LI) Bedrock Aquifer. Towards the eastern boundary of the scheme area the underlying bedrock is Waulsortian mudbank formation which is a pale-grey massive unbedded limestone and mudstone and is classified as a locally Important Aquifer whose bedrock is moderately productive only in local zones. The GSI bedrock aquifer types map is presented in Figure 2-2. The vulnerability of the groundwater aquifer is presented in Figure 2-3 and is indicative of the depth of overburden cover. The overburden depth interpreted from the GSI groundwater vulnerability mapping shows generally moderate to deep overburden depths associated with high (3 to 5m overburden depth, medium vulnerability (5 to 10m overburden depths) and low Vulnerability (> 10m overburden depths).

The GSI 1 in 50,000 scale quaternary map showing the sediments mapped within 1m of the ground surface and categorized according to their genesis is presented in Figure 2-4. The predominant sediments within the scheme area are Limestone tills with other deposits comprising cut-over raised bog, extensive alluvial deposits along the River Suck basin, gravels derived from limestones and esker gravel deposits. The general soil permeability is presented in Figure 2-5. The quaternary is variable within the Scheme area with the more permeable limestone till to the west of the Suck Floodplain area and north of the M6 road at Pollboy with high annual recharge rates varying from 300 to 500mm, refer to Figure 2-6. To the East and north the quaternary is variable with alluvial deposits, limestone till and gley soils having a moderate to low recharge rates of 100 to 150mm per annum. South of the M6 Road extensive peat deposits are present with poor groundwater recharge rates, indicating high runoff and low soil and sub-soil infiltration..

A review of the OSI Historical 25inch mapping for the scheme area shows no obvious karst surface features or localized liable to flood lands associated with turloughs. There is a localized depressional area to the east of the Creagh Road (R357) which suffers from localized flooding. This flooding is associated with local drainage of lands discharging to a small drain that outfalls to a stone culvert that crosses under the R357. The invert to the culvert is slightly more elevated than the surrounding land and therefore ponding occurs in the lower lying lands to the east of the Graveyard during prolonged wet periods when infiltration rates are exceeded. In the past due to blockage to this culvert the floodwaters have flooded across the R357 road. The groundwater table is likely to be close to ground level in these low-lying lands such that for prolonged wet periods infiltration is very limited and ponding occurs. This is primarily a pluvial flooding issue as opposed to groundwater.

The majority of the scheme area has surface drains or in the built areas storm drainage linking it the adjacent rivers and streams and does not suffer from any significant groundwater flooding and specifically from karst flooding. In conclusion this review of Groundwater flooding within the scheme area of Ballinasloe indicates that groundwater induced flooding is not a significant factor in flooding at Ballinasloe.

A fault line is mapped by the GSI running in an East–West orientation intercepting the rail bridge crossing of the River Suck, refer to Figure 2-1. Often such fault lines can lead to a zone of preferential groundwater flow pathway due to potentially increased fracturing and fissuring of bedrock leading to increased solutionization and weathering.
The 25inch mapping does not suggest any zone of transmission in respect to any mapped springs and swallow holes in the vicinity of this fault line.

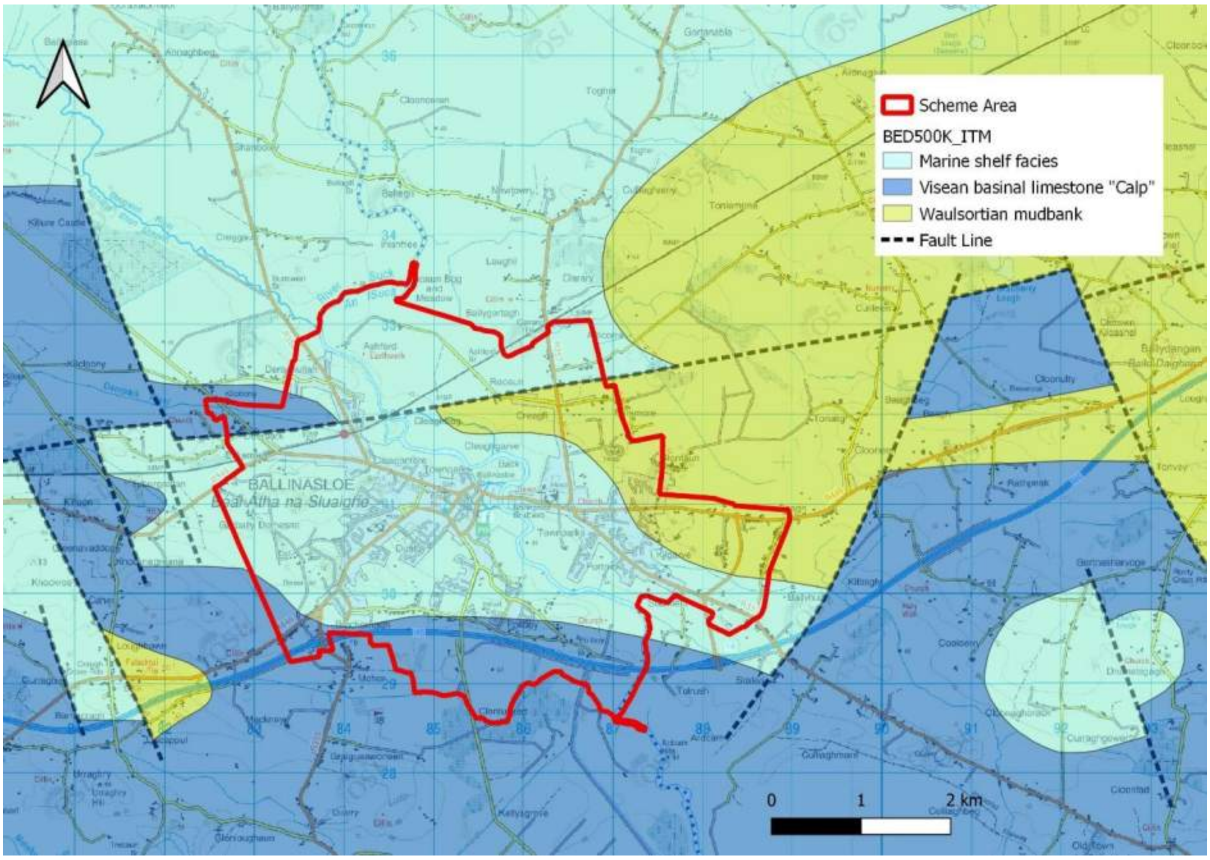

Figure 2-1 Bedrock Classification Mapping for Ballinasloe area

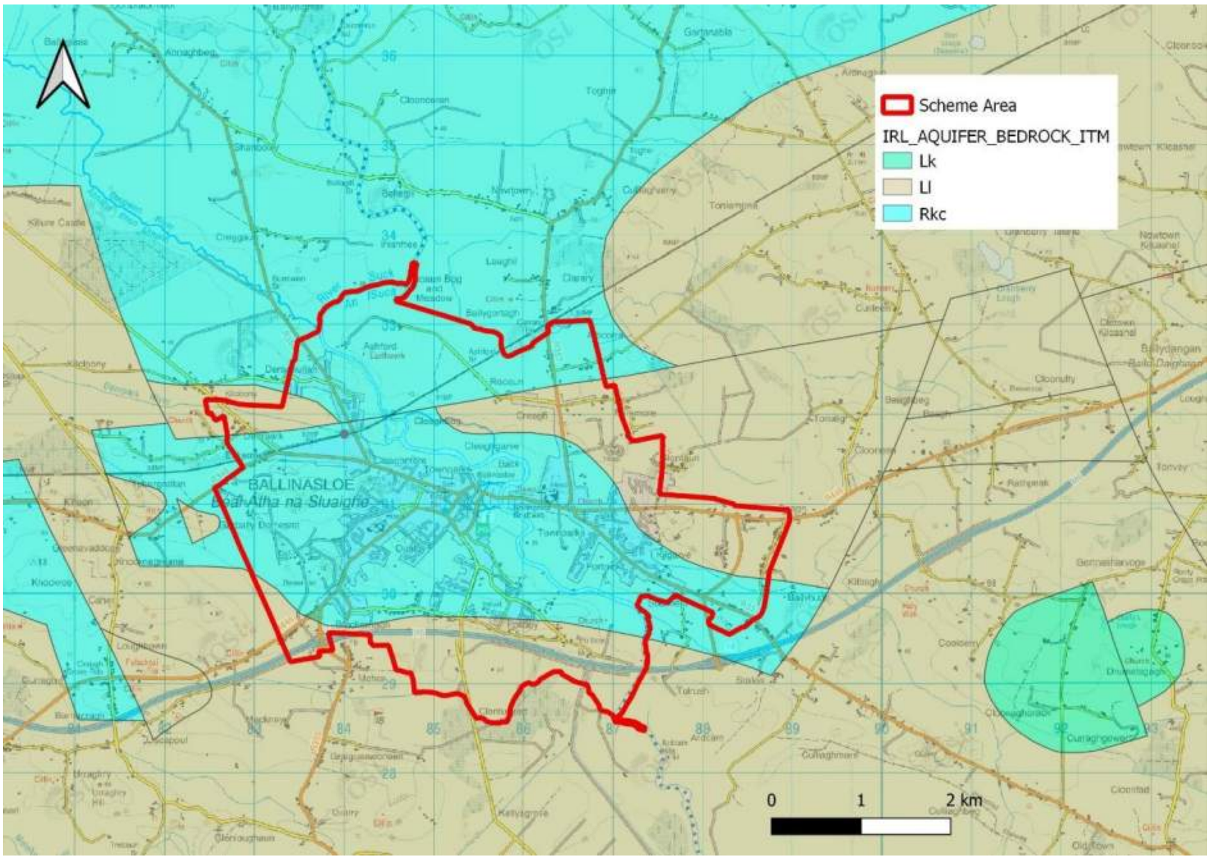

Figure 2-2 GSI Bedrock Aquifer Classification

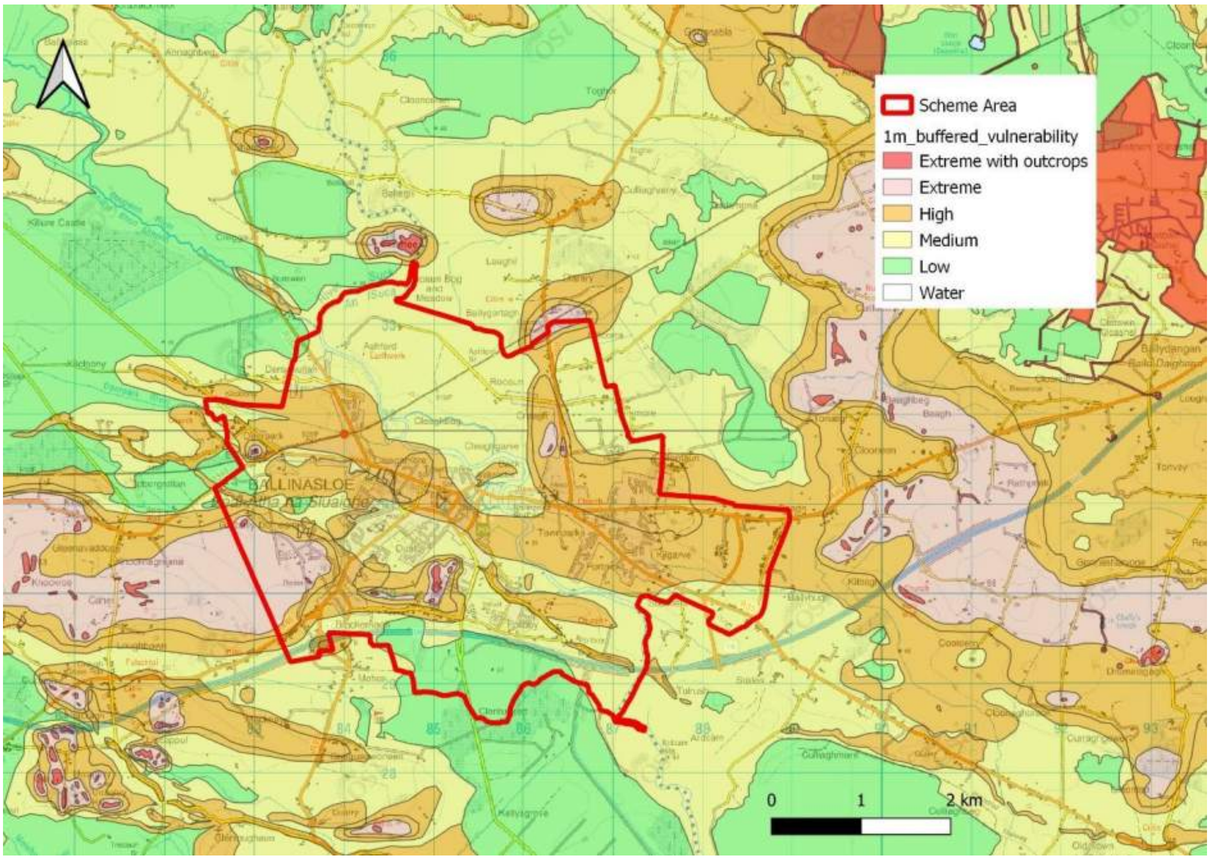

Figure 2-3 Groundwater Vulnerability Mapping indicative of overburden depths

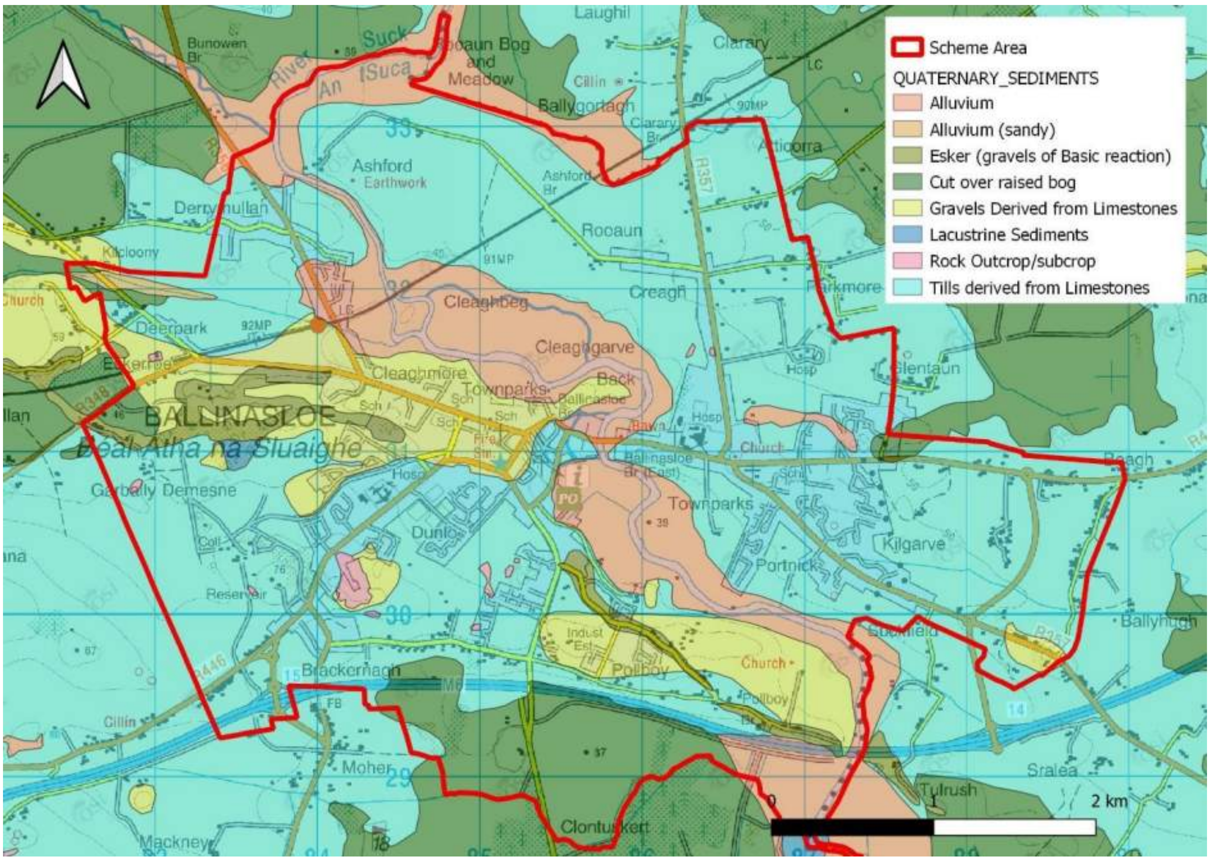

Figure 2-4 Quaternary Deposits

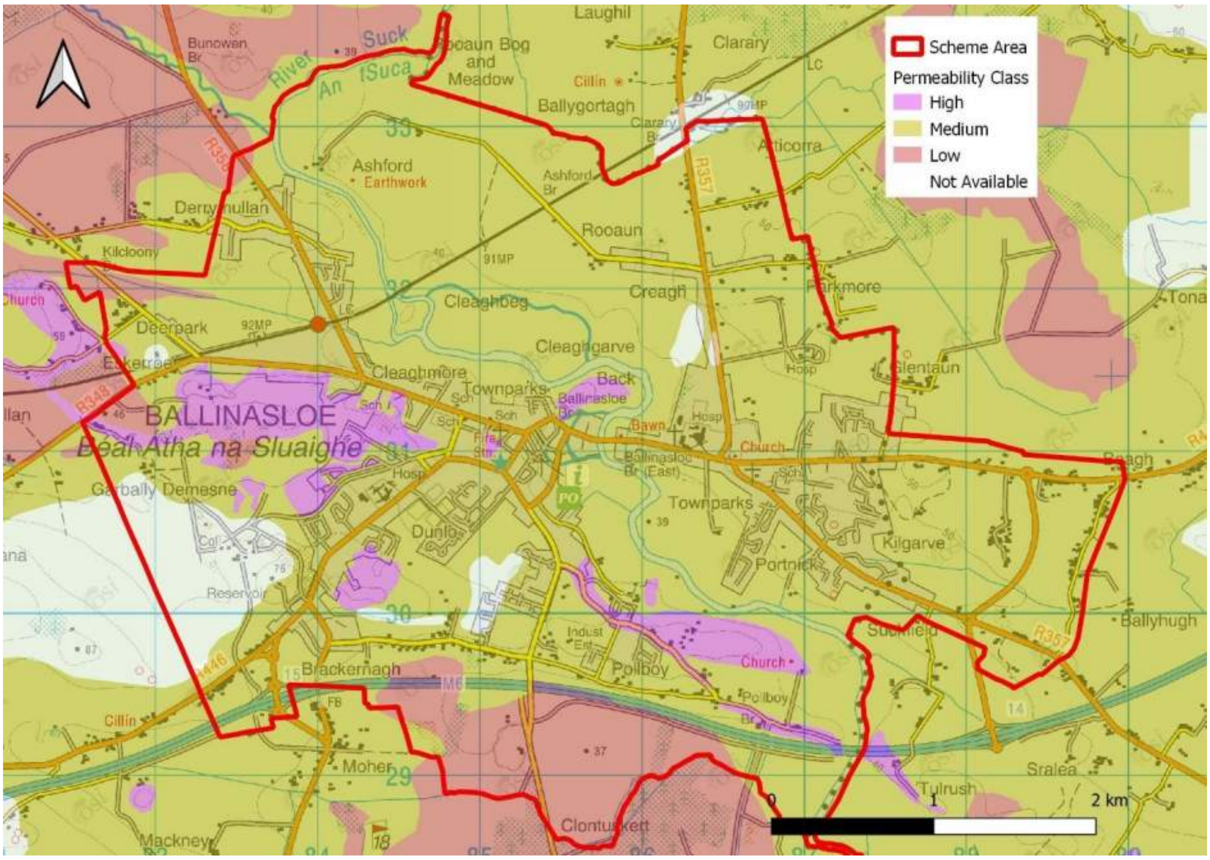

Figure 2-5 Sub-Soil Permeability

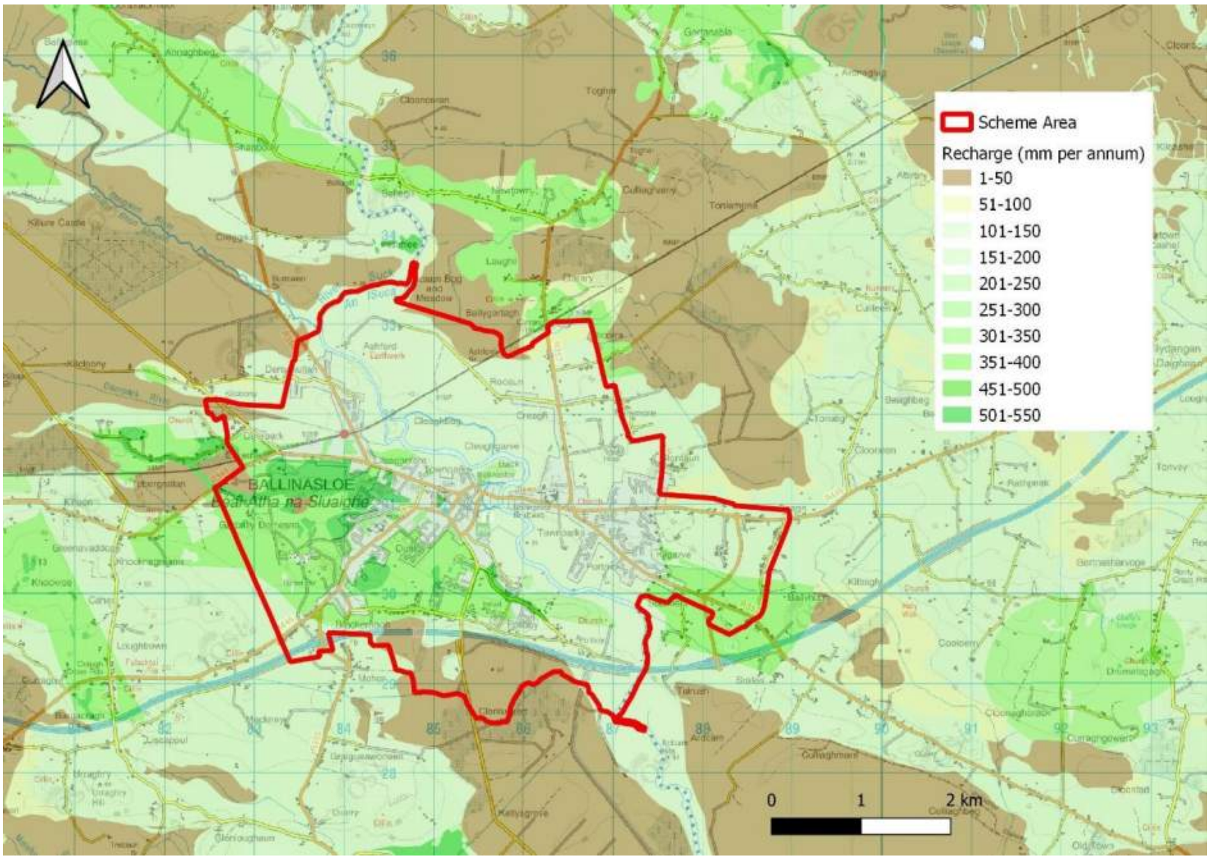

Figure 2-6 Groundwater recharge rates based on quaternary type and bedrock

2.5 Review of Pluvial Flooding

The topography of the scheme area at Ballinasloe is variable with a wide flat basin area through the middle of the scheme area running northwest to southeast associated with the Suck floodplain area and the Bunowen River basin. Flanked to the southwest and southeast is higher ground which is undulating, associated with glacial deposits and bedrock. A number of local raised features associated with esker deposits are present on the western side of the Suck basin. The Suck Basin area has a shallow water table influenced by river levels, whereas in the free draining till and limestone gravel raised areas to the west of the scheme reasonably good infiltration rates exist and the groundwater table is at depth.

Based on 5m lidar topographical data, refer to Figure 2-7 local depressional areas were identified and are presented in Figure 2-8 to Figure 2-10. The likely build-up and ponding of effective rainfall from storm events in these areas will be further assessed in the hydraulic model based on rainfall depths presented in Table 2-6 and groundwater recharge rates presented in Figure 2-6. Potential defended areas are likely to be affected by pluvial events and will require assessment to ensure pluvial risk is not increased behind any fluvial defences. The 2-D element of the hydraulic flood model for Ballinasloe will examine potential pluvial flood areas further depending on the measures proposed.

Rainfall depths using the Met Eireann storm rain Frequency Duration Intensity model developed for the FSU provides the following point estimates in Table 2-6 for Ballinasloe (National Irish Grid E184000, N230000).

Table 2-6 Met Eireann Frequency Duration Depth estimates for node point at Ballinasloe Grid reference ING E184000, N230000

	Return Period								
Duration	**2yr**	**5yr**	**10yr**	**20yr**	**30yr**	**50yr**	**100yr**	**150yr**	**200yr**
0.25	6.9	9.9	12.2	14.7	16.4	18.8	22.5	24.9	26.9
0.5	8.9	12.3	14.9	17.8	19.7	22.3	26.4	29.1	31.2
1	11.4	15.4	18.4	21.6	23.7	26.6	31	33.9	36.2
2	14.5	19.2	22.6	26.2	28.5	31.7	36.5	39.6	42
3	16.8	21.9	25.5	29.4	31.8	35.2	40.2	43.4	45.9
4	18.6	24	27.8	31.8	34.4	37.8	43	46.3	48.8
6	21.5	27.3	31.4	35.6	38.3	41.9	47.3	50.8	53.4
9	24.9	31.1	35.4	39.9	42.8	46.5	52.1	55.7	58.3
12	27.5	34.1	38.6	43.3	46.2	50.1	55.8	59.4	62.1
18	31.8	38.8	43.6	48.5	51.5	55.6	61.4	65.1	67.9
24	34.9	42	46.9	51.9	55	59	64.9	68.6	71.3
48	42.7	50.6	55.9	61.2	64.5	68.8	75	78.8	81.7
72	49.4	57.9	63.6	69.4	72.8	77.4	83.9	87.9	90.9
96	55.5	64.6	70.7	76.7	80.4	85.1	92	96.2	99.3
144	66.5	76.7	83.3	90	94	99.2	106.6	111.2	114.5
192	76.6	87.7	94.9	102	106.3	111.9	119.8	124.7	128.3
240	86.1	97.9	105.6	113.3	117.8	123.8	132.2	137.3	141.1
288	95.1	107.7	115.9	124	128.8	135	143.8	149.2	153.2
384	112.3	126.3	135.3	144.1	149.4	156.2	165.8	171.6	175.9
480	128.6	143.8	153.6	163.1	168.8	176.1	186.4	192.6	197.2
600	148.2	164.9	175.5	185.8	191.9	199.8	210.9	217.6	222.5

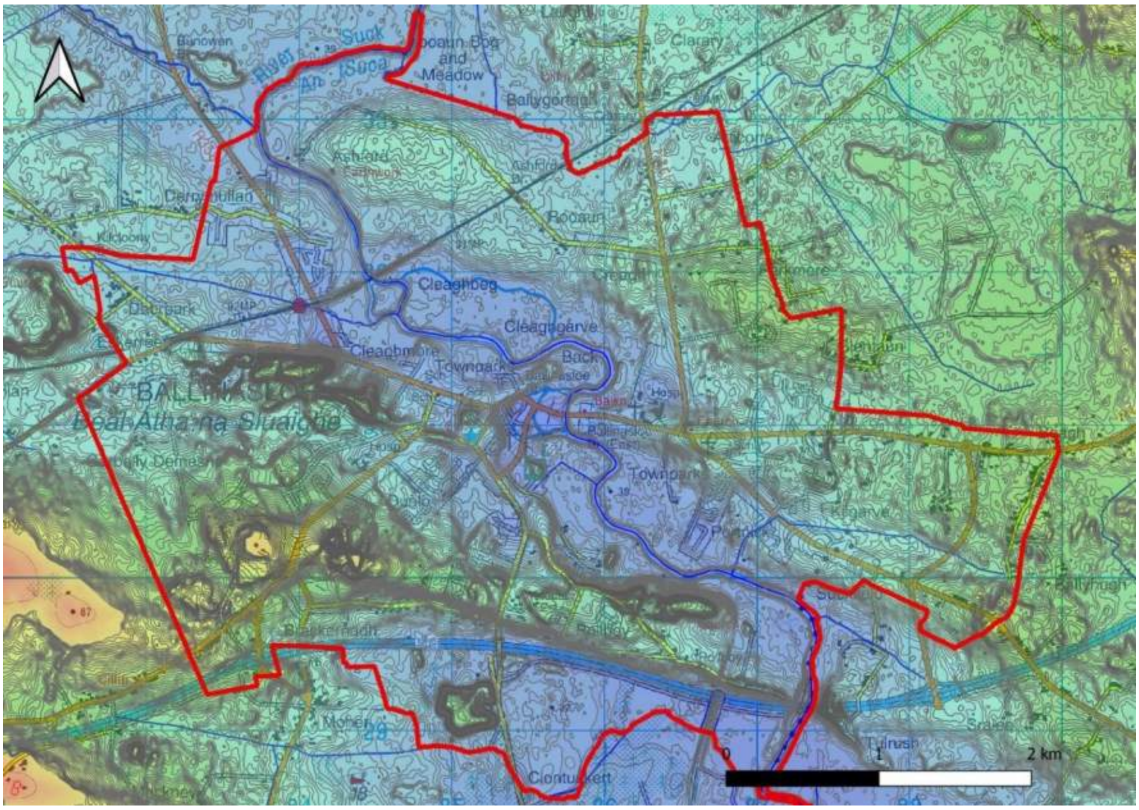

Figure 2-7 Ground surface contours from 5m LidarIntermap data.

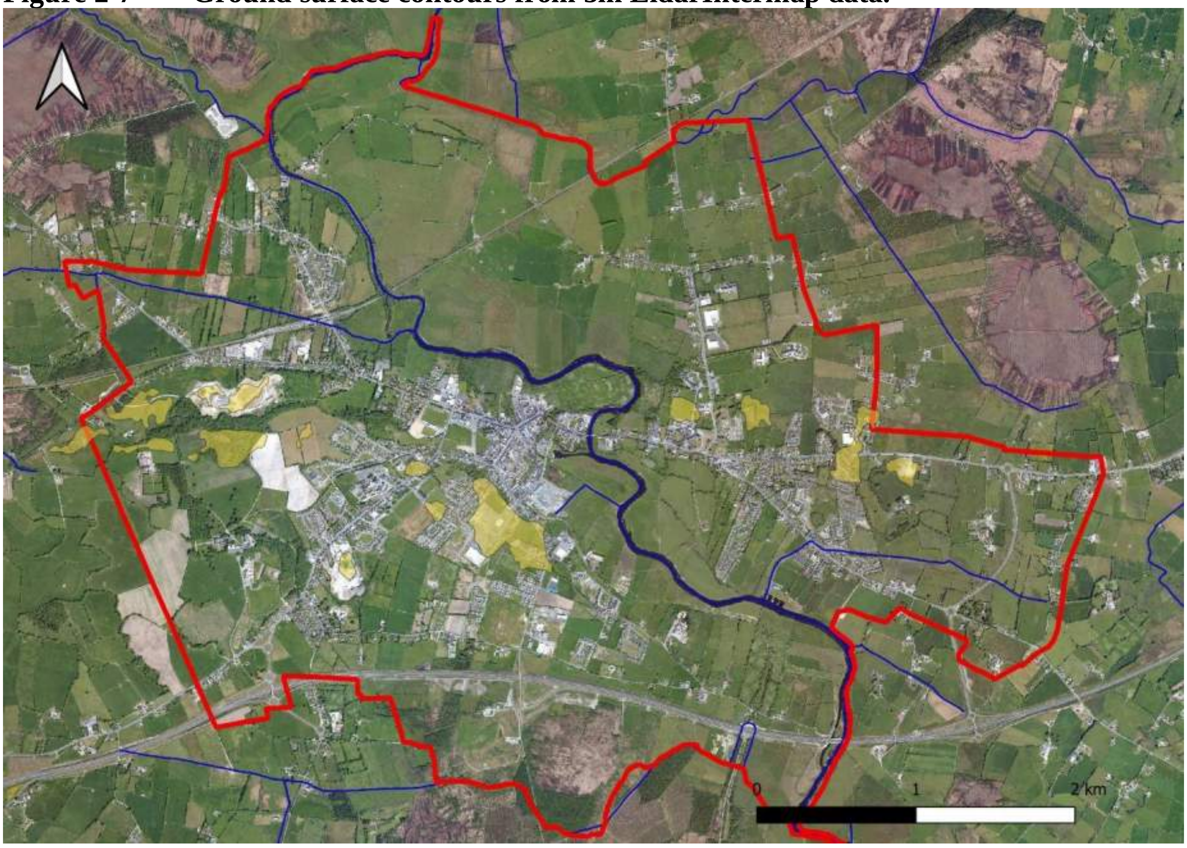

Figure 2-8 Screening for Local Depressional feature with potential for pluvial flooding – Scheme Area

Figure 2-9 **Screening for Local Depressional feature with potential for pluvial flooding - Western Section**

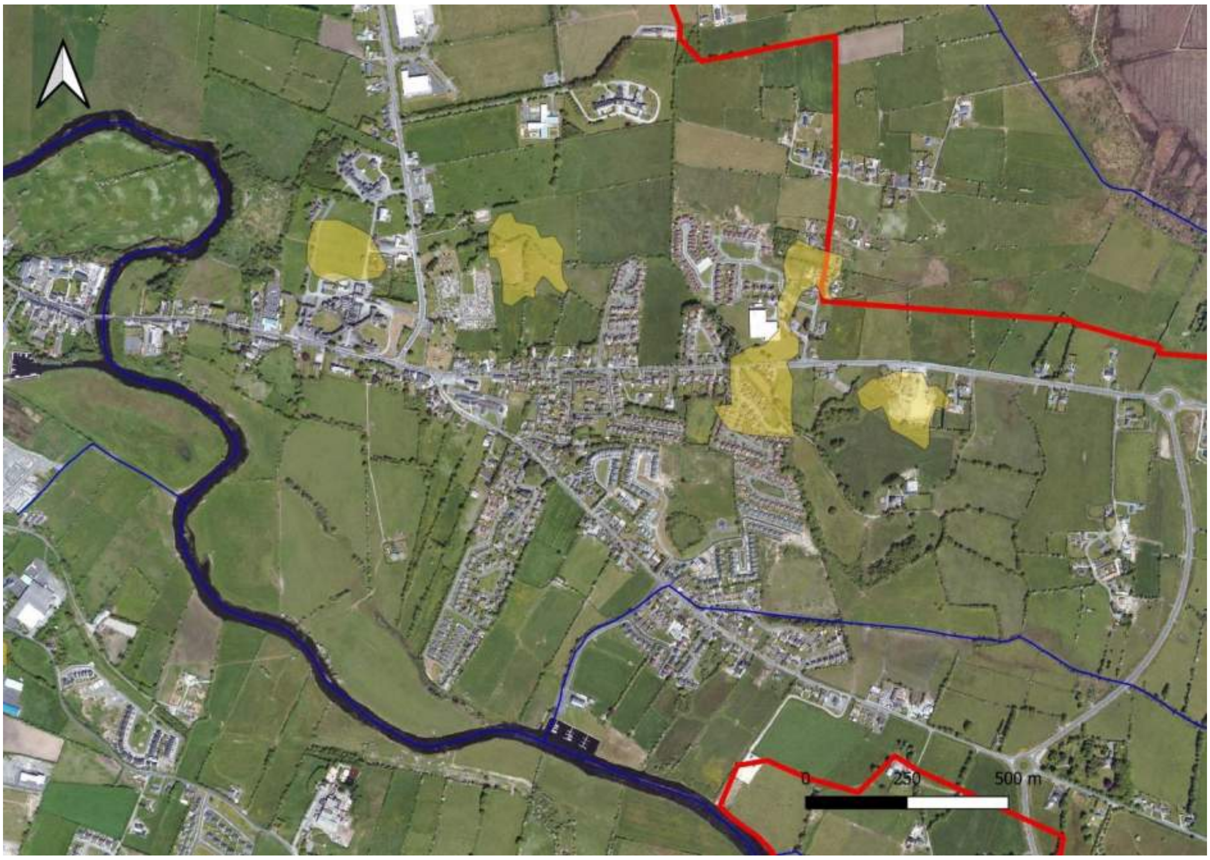

Figure 2-10 **Screening for Local Depressional feature with potential for pluvial flooding - Eastern Section**

3 Hydrometric Data Collation and Review

3.1 Past Flood Events

3.1.1 Past Flood Events

A review of historical flood events identified significant flooding associated with the following years at Ballinasloe from the River Suck. The River Suck at Bellagill (26007), 2km upstream of Ballinasloe has a long record of water level and flow estimates with continuous records since 1952 (68year record). Based on this reliable record of annual maximum floods the 10 largest floods are ranked as follows:

Table 3-1 Highest recorded flood flows and level on the River Suck at Bellagill

Flood Rank	Hydrometric Year	Elevation m OD poolbeg	Peak Flow (cumec)	Date	Estimated Return Period (years)
1	2009	43.292	212.5	21/11/2009	202
2	2015	43.192	192.4	07/12/2015	113
3	1968	42.924	145.1	05/11/1968	21
4	2019	42.917	144.0	25/02/2020	20
5	1954	42.86	135.1	20/10/1954	13.5
6	2006	42.82	129.1	08/12/2006	10
7	1999	42.78	123.3	29/12/1999	7.5
8	1989	42.76	120.5	08/02/1990	6.5
9	2017	42.738	117.4	26/01/2018	6
10	1957	42.73	116.3	15/02/1958	5.5

The return period is based on single site statistical analysis and does not reflect the design return periods presented latter in Section 11 which used a pooled growth curve

The three largest events from Table 3-1 are discussed in more detail in the following subsections. It should be noted that the more recent 2009 and 2015 floods were significant floods in comparison to the other ranked floods as indicated by their estimated return periods and these floods resulted in significant flooding of properties, whereas the other flood events had much smaller affect.

These flood events will be used in the calibration and validation of the hydraulic flood model for Ballinasloe with the historical largest November 2009 flood event used to calibrate the model and the other events used to verify model as fit for use in a predictive capacity. The December 2015 flood event will include for the recent changes to lift gates on Ballinalsoe Bridge which were cut and lifted as advance flood relief works in response to the November 2009 Flood Event.

3.1.2 November 1968

The peak of the November 1968 flood event occurred on the 5th of November. Anecdotal observations identified that the flooding in the Townparks area came to the steps leading up to St. Michaels Church. At Bellagill the recorded peak flow rate was 145.14cumec, which based on statistical analysis represents approximately a 20year return period flood event, based on the record to date.

Daily rainfall from MET rain gauges for the Suck catchment was complied for this event which saw moderately persistent rainfall of almost one month culminated in heavy 2-day daily rainfall amount at the end of the event on the 1st November 1968. The daily rainfall profile for this event is presented below in Figure 3-1.

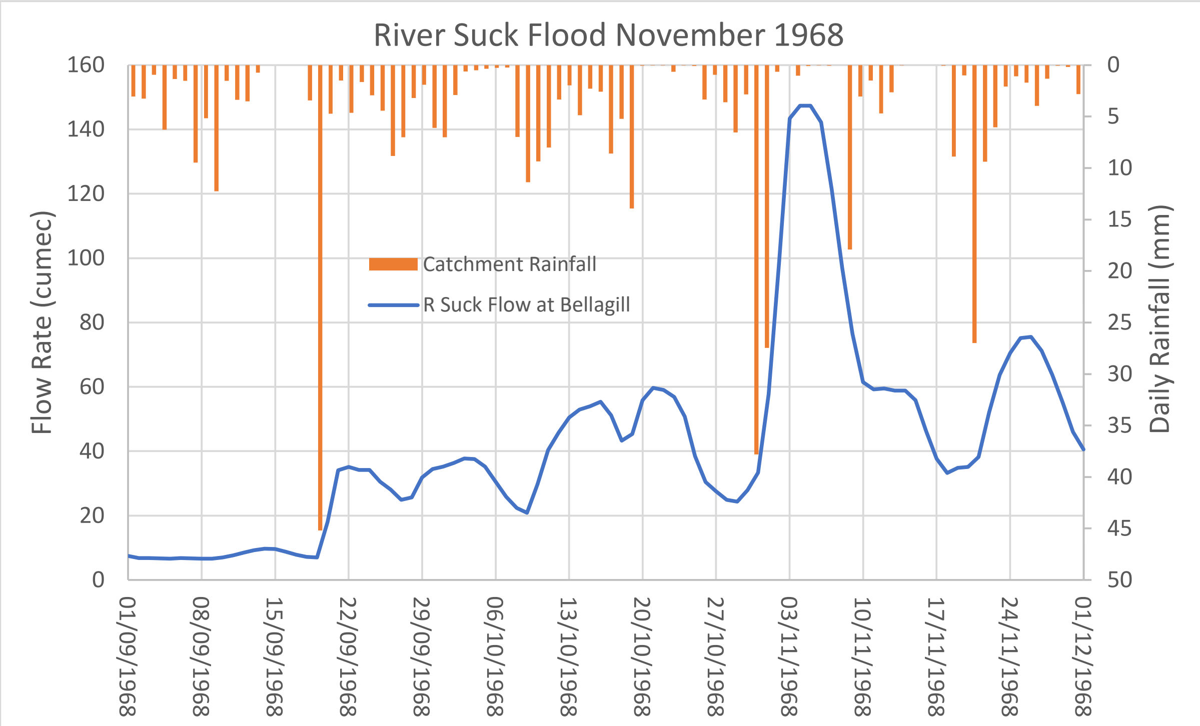

Figure 3-1 Recorded rainfall and River Suck Flow at Bellagill for November 1968 Flood Event

An analysis of the recorded rainfall totals at different durations was carried out to determine the return period and is presented in Table 3-2 below. This analysis found that the estimated return periods were a maximum of 16years at a 2day duration and reducing to c. 2year at longer durations. Of interest is that the rainfall ceased by the 2nd of November, whereas the flood peak did not arrive until 4th and 5th of November suggesting a delayed and attenuated response to the rainfall event in 1968.

Table 3-2 Recorded rainfall depth duration and return period for the November 1968 Flood Event

Rain Duration days	Catchment Rain depth mm	Estimated Return period years
1	37.8	3
2	65.3	16
3	68.1	10
5	78.3	6
10	91	2
15	122.2	3
20	125.1	1.5
25	162	2

The above rainfall analysis shows that the antecedent rainfall prior to the flood peak had a relatively low return period of 2years (at 25day duration) followed by 2days having a return period of 16years produced a flood peak on the Suck at Bellagill station of 21years. This event was much more flashy rising and falling over an eight day period in comparison to the much longer floods and larger flood volumes recorded in 2009 and 2015.

3.1.3 November 2009

The November 2009 flood event historically is the most significant flood event for the Ballinasloe area in the 68year record period with the recorded flood peak at Bellagill based on the revised rating relationship estimated to be 212.5cumec occurring on the 21st November 2009. Based on at-site statistical analysis of the 68year AM flood flow record this event represents c. a 200year return period event which is very significant. The rainfall profile from 8 available MET rain gauges for the Suck Catchment is presented in Figure 3-2. This clearly shows that the flood event commenced on the 19th of October and continued to the 27th of November in terms of prolonged rainfall with the peak flow rate recorded on the 20th/21st of November as a result of heavy rainfall falling on the 17th, 18th and 19th of November on top of an already saturated catchment. The recorded rainfall depths over the catchment area at the longer durations of 5 to 25days have estimated return periods increasing from 100 to 400years respectively. The impact of such a saturated catchment is to increase the percentage runoff rate for overland flow to the rivers and streams and also to reduce the attenuation storage effect of the large floodplain areas along the River Suck.

An analysis of the recorded rainfall totals at different durations was carried out to determine the associated return periods and is presented below in Table 3-3. This analysis found that the estimated return periods were modest at 3 year at the 1 day, 20 year at the 2day and 50 year at the 3 day rain storm durations. What makes this event so significant as to have an estimated return period of 200year is the combination of prolonged rainfall with the sharper 2/3 day rainfalls to produce significantly elevated runoff rates over previous events (such as the 1968 flood event). The November 1968 event did not have such significant antecedent rainfall conditions leading up to the heavy two day rainfall and thus a significantly lower flood peak and hydrograph volume recorded at Bellagill in 1968.

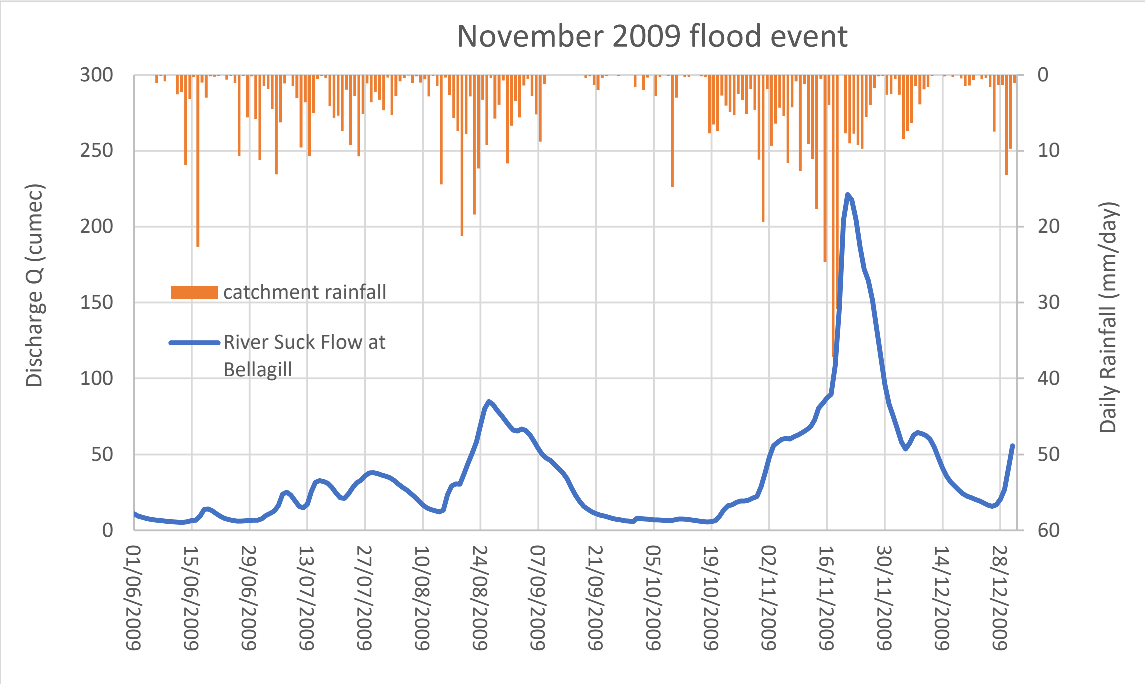

Figure 3-2 Recorded rainfall and River Suck Flow at Bellagill for November 2009 flood Event

Table 3-3 Recorded rainfall depth duration and return period for the November 2015 Flooding (leading up to peak flood flow rate on the 21st November 2009)

Rain Duration days	Catchment Rain depth mm	Estimated Return period years
1	37.2	3
2	68.0	20
3	89.7	51
5	118.3	100
10	164.4	152
15	205.8	238
20	236.4	234
25	279.0	400

3.1.4 December 2015

A peak flow of 192.4cumec was recorded in the River Suck on the 7th December 2015. The at-site statistical analysis indicates that such a flow rate is very significant with a return period of 108 years.

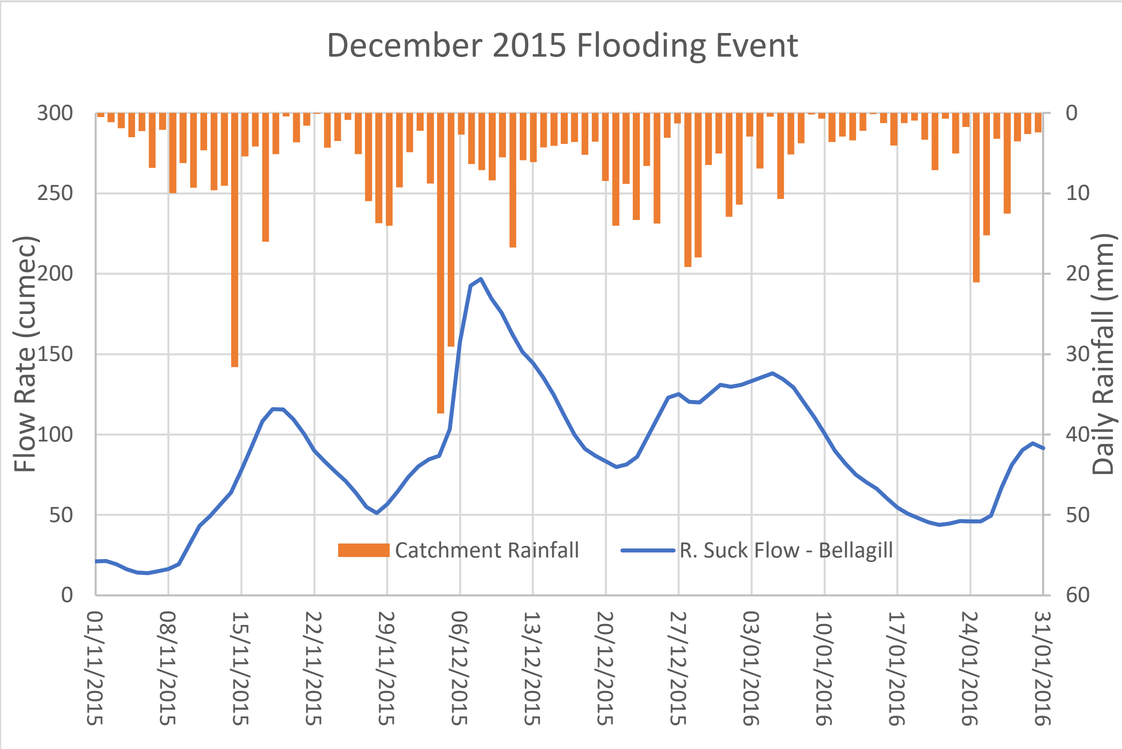

Figure 3-3 Recorded rainfall and River Suck Flow at Bellagill for December 2015 flood Event

The rainfall profile determined from 12 available daily read MET gauges for the Suck Catchment shows prolonged rainfall from November through to February with the flood hydrograph displaying four distinct hydrograph peaks, each of which were in excess of the annual maximum flood (2year Flood) and were associated with the rainfall pattern, refer to Figure 3-3.

An analysis of the recorded rainfall totals was carried out to determine the associated return periods at different rainfall durations leading up to the flood peak on the 7th December and is presented below in Table 3-4. This analysis found that the estimated return periods were quite modest at 3year at the 1day, 18year at the 2day and 17year at the 3day rain storm durations. The longer durations leading up to this event are also only modest return periods in comparison to the estimated return period of 108year for the flood peak. The rainfall data would suggest that the actual return period of this flood event is considerably lower than the flood frequency analysis estimate of 108years.

Table 3-4 Recorded rainfall depth duration and return period for the December 2015 Flooding (leading up to peak flood on the 7th December 2015)

Rain Duration days	Catchment Rain depth mm	Estimated Return period years
1	37.4	3
2	66.5	18
3	75.2	17
5	82.3	8
10	135.4	30
15	145.7	9
20	175.0	12
25	235.3	60

This event, similar to the other events, requires typically a two-day intense rainfall following a period of prolonged rainfall. In some ways, the December 2015 event could have been far worse if the higher intensity 2-day rainfall had arrived towards the end of December after a period of more prolonged rainfall instead of it arriving in early December. It is also evident similar to the 2009 flood event that the peak flooding required the combination of prolonged rainfall immediately followed by more intense rainfall over c. 1 or 2 days.

It is important to note that the 2015 flood event is the second flood event in a 6-year period that exceeds the estimated 100year flood magnitude. This occurrence prompts a degree of caution when selecting the design flood magnitude for this flood relief scheme from the historical data as it may suggest a change in the characteristics of flooding (increasing trend of flood magnitudes) and potentially that the flood events on the River Suck are no longer represented by a single statistical distribution, which is a requirement for the governing statistics behind the flood frequency analysis.

3.2 Hydrometric data collation

All relevant and available hydrometric data has be collected and reviewed, which includes the following stations presented here in Table 3-5.

Table 3-5 Hydrometric Station references to be used in the flood estimation methods and in constructing a flood growth curve pooling group

Hydrometric Gauge References				
26007	25006	16008	36010	07010
26005	25011	16009	36019	07004
26002	25027	16002	36016	06012
26006	25020	16011	35005	29001
26108	25022	16006	30004	29011
26010	25044	15012	30012	
26018	25029	15002	30007	
26020	25014	15006		
26027		15004		

The majority of the above stations are used in the pooling group analysis for estimating flood growth curves which is described in detail in Section 5 flood flow estimation.

3.3 Rating Review

3.3.1 Introduction

The OPW Rating classifications developed for the Flood Study Update and continued to be used are described as follows:

- A sites – sites that had stage-discharge ratings that were considered good for determining high and flood flows. The A sites were then sub-divided into:
  - A1 sites – Confirmed ratings good for flood flows well above QMED with the highest gauged flow greater than 1.3 x QMED and/or with good confidence of extrapolation up to 2 times QMED, bankfull or, using suitable survey data, including flows across the flood plain.
  - A2 sites – Ratings confirmed to measure QMED and up to around 1.3 times the flow above QMED. Would have at least one gauging to confirm and have good confidence in the extrapolation.

- B sites – sites that had good high flow ratings, but where there were some concerns over the flood flow ratings. The B sites – Flows can be determined up to QMED with confidence. Some high flow gaugings must be around the QMED value.

- C sites – sites that had reasonable medium to high flow ratings, where it was not possible to determine flood flows with any confidence due to the fact that at high flows, the site was either not rateable or there were insufficient gaugings to produce a rating. The C sites – Sites within the classification have the potential to be upgraded to B sites but require more extensive gauging and/or survey information to make it possible to rate the flows to at least QMED.

- P sites – these were classified as poor and were not considered suitable for high and flood flow determinations. It is possible that some of these sites could be used in future if sufficient gaugings and other information were available.

- U sites – these are sites where the data would be totally unusable for determining high flows. These could, for example, be level only sites where it is not possible to measure discharges and thus develop stage-discharge relationships.

The criteria for the classification referred to above was mainly the ratio of the highest gauged flow (HGF) to the estimated QMED, thus: $Ratio = \frac{HGF}{QMED}$

The classification also took into account the uncertainty of QMED from the gauging at a 95-percentile confidence interval.

Uncertainty classification
< ± 10% Very good
± 10 – 30 % Good
> ± 30% Fair

The estimated uncertainty in the estimated value of QMED should be within ± 10% of the true value at the 95% confidence level for A1 rated stations and <30% for A2 rated gauging stations.

It is not clear how this was accounted for in the FSU as many of the classified A1 gauges used in the FSU had greater uncertainty than 10% based on the scatter of gaugings or the absence of higher flood flow gauging's.

Rating relationships from the measured Stage – Flow rating data for River Suck at gauges 26007 and 26005 are reviewed and reported on in this section of the hydrology report. To assist the review, hydraulic modelling using the original CFRAM river channel and floodplain cross-sections and additionally surveyed cross-sections was carried out.

Hydraulic modelling (survey, develop and calibrate local models) for a number of stations (namely Bellagill and Derrycahill) simulating the flood stage-discharge relationship was performed in order to extend the rating relationship and identify and include any bypass flows, where they exist.

The following Table 3-6 presents the current OPW quality classification of the River Suck hydrometric stations for flood flow estimation.

Table 3-6 Flood Rating Quality Classification for Suck River Hydrometric Stations (OPW)

Site	Station Ref No.	OPW Rating Quality	Area km^2
Bellagill	26007	A1	1207
Derrycahill	26005	A2	1084
Rockwood	26002	A2	642
Willsbrook	26006	A1	185

A1 = Excellent *A2 = Good*

This classification is flawed as it is classified based on the magnitude of the maximum rated flood flow relative to the annual maximum flow as defined by the median flood flow and not on the scatter / variation of the measured flow or on the number of higher flood measurements available in the rating set.

3.3.2 Rating Review Bellagill (26007)

Rating data involving measured flows (by velocity area method) and measured stage have been gathered by the OPW since 1947 to date and OPW Hydrometrics have provided this data for the Bellagill gauge. This has provided a significant set of rating measurements up to and including 2020. The flood rating data (i.e. above 39mOD) for Bellagill is plotted inFigure 3-4. This station has an A1 rating and has a good ratio of highest gauged flow to QMED with a ratio of 2.1. This represents an extensive rating range and provides for good certainty in the extrapolation of rating relationship for bigger floods.

These rating measurements shows a sizable degree of scatter about a best-fit power curve ($Q=aH^b$), refer to Figure 3-5, suggesting a potential higher degree of uncertainty than the OPW hydrometric quality rating of excellent, A1 (quality rating latest review in 2017) might suggest. The larger spread of the rating occurs at the 90 to 140 cumec flow range, which is likely to be associated with variability in out of bank floodplain conveyance efficiencies and downstream floodplain storage and attenuation effects.

Above 150cumec flow magnitude, only one single measurement of peak flow was captured, and this was on the 23rd of November 2009 at 196.4 cumec, for a 3.1m stage height. The recorded peak occurred earlier on the 21st November at 3.172m but the hydrograph remained almost flat for a number of days and therefore represented a gauging reasonably close to the peak. With only one measurement above 150cumec, it is impossible to quantify the degree of spread in the rating data at this higher flow magnitude. However, one would suspect that the natural causes of measurement spread is from out of bank flow conveyance and downstream attenuation effects (aside from measurement accuracy) which are variable with conveyance more efficient and attenuation effects diminished at the larger overbank flow depths.

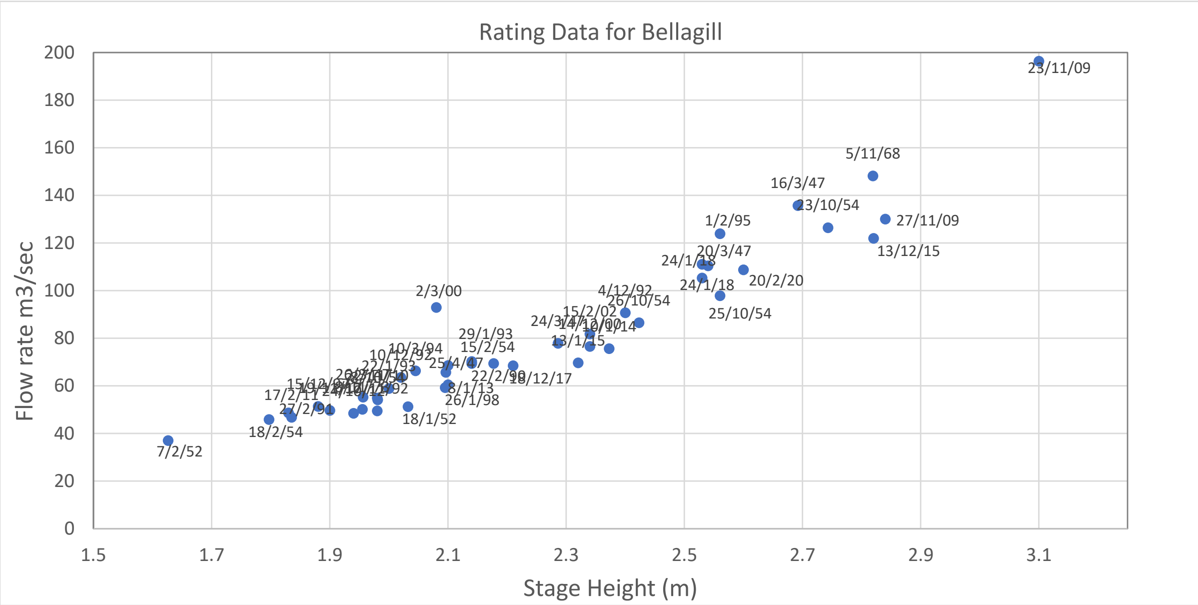

Figure 3-4 Current extent of Bellagill Flow-Stage Rating Data (up to March 2020)

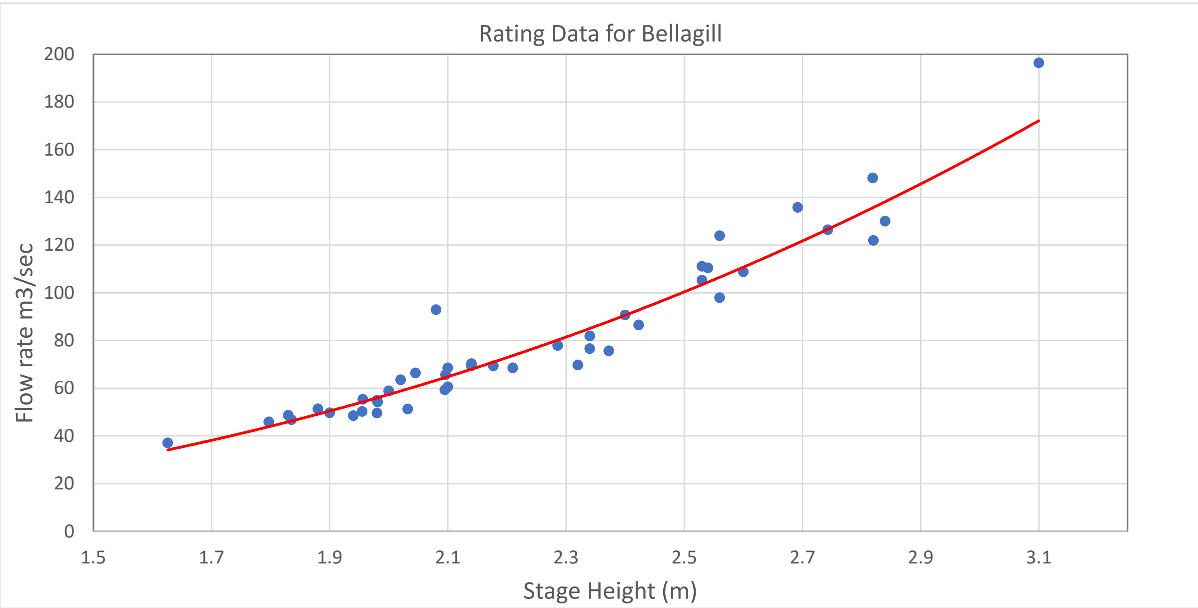

Figure 3-5 Bellagill Flow Rating Data with best fit Power Law

It should be noted that a single rating outlier associated with measurement carried out on the 2nd March 2000 is eliminated from consideration as it suggests measurement or recording error.

The OPW rating that is currently in use by their hydrometric section is based on the gauge rating data measured pre 2005 and therefore does not include rating data gathered during the recent large floods of November 2009 and December 2015. This rating relationship is presented below in Figure 3-6 with the more recent measurements included for comparison. Based on the 23rd of Nov 2009 flow measurement, this indicates an overestimation by some 10cumes, which is within the percentage measurement error of the recorded value.

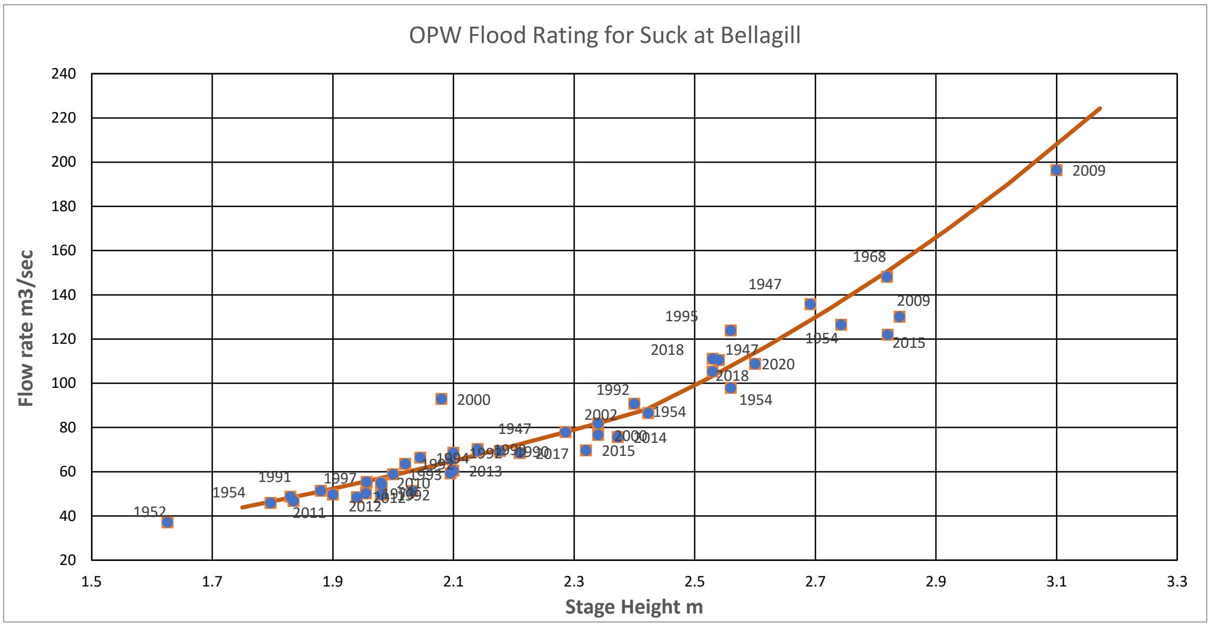

Figure 3-6 Existing OPW Rating Relationship for the Bellagill gauge

As part of the CFRAM study carried out by Jacob's for the Shannon Basin, including the Suck River a rating review was carried out. This review retained the current OPW ratings at Bellagill, refer to Figure 3-7 which was extracted from the CFRAM Upper Shannon Hydrology Report (Jacobs, 2016). The CFRAM hydraulic modelling showed a more efficient rating relationship having generally smaller stage producing bigger flows over the OPW rating. However, the examination of Figure 3-7 shows that the modelling does not represent well the middle range of the flow data.

The staff zero datum for Bellagill is recorded by the OPW at 40.12m OD Poolbeg. On the 21 March 2012 Murphy Survey Ltd. as part of the CFRAM river channel survey measured a datum zero for the Bellagill gauge of 37.409m OD Malin (ING02) (This represents a conversion from Poolbeg to Malin of -2.711m). As part of the rating review for this study, Murphy Surveys Ltd. again measured the staff gauge datum at 37.325m OD Malin02 (representing a conversion from Poolbeg to Malin of -2.795m), 8.4cm lower than the previous survey on the 20th May 2020. A check of the surveys found that the recorded soffit levels for the Bellagill bridge arches were reasonably similar at c. within 1 to 2cm from both surveys. As a second check the surveyed water level at the gauges was 38.19m OD on 21/03/2012 12:02 and the OPW gauge gave a water level for that date and time of 40.9m OD Poolbeg which is consistent with the measured staff zero of 37.409m OD. The surveyed water level at the gauge site on the 20 May 2020 11:28am was recorded as 37.984m OD Malin and the OPW hydrometric record from the gauge gives a water level of 40.764m Poolbeg which gives a staff zero of 37.35m OD which is reasonably close to the measured staff zero on that date of 37.325(1.75cm higher). The most recent Surveys staff zero of 37.325m OD Malin is used in this study. It is recommended that

OPW Hydrometric should considered carrying out a more detailed staff datum survey over a period to eliminate any potential error.

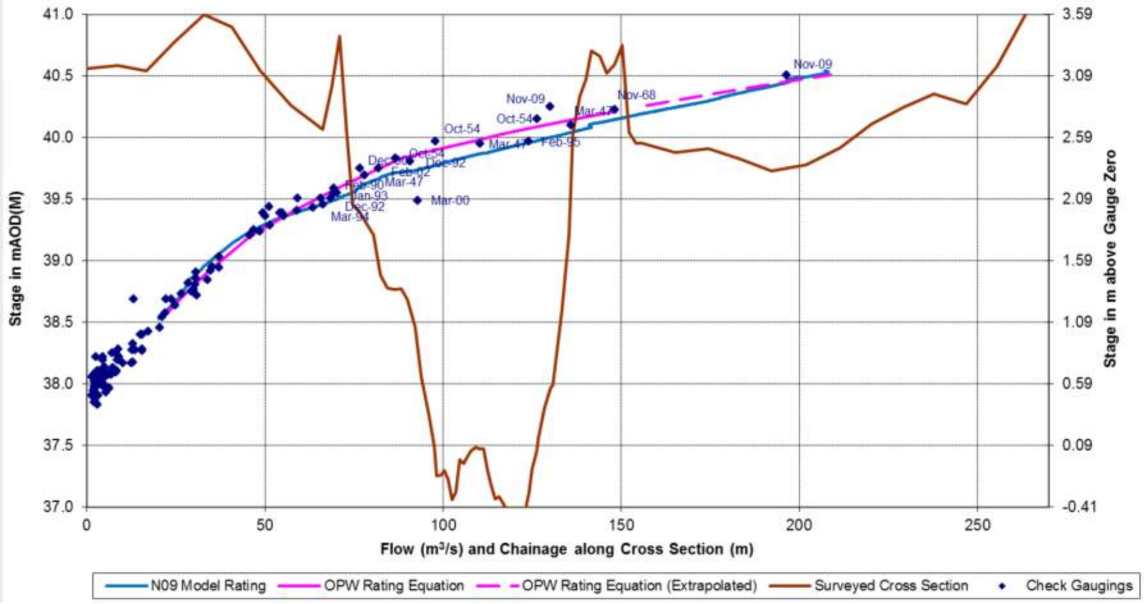

Figure 3-7 CFRAM Study Rating Review of Bellagill Gauge (26007) with modelled rating

The rating review for this study includes the entire data set from 1947 to March 2020. A review of this data does not identify any temporal changes of significance in the rating relationship and therefore concludes that the full rating data series (1947 to 2020) is valid for use in establishing a revised rating. Specifically, the rating review considered the rating data from 1990 onwards against the entire data set and found little difference in the power-law fit; refer to Figure 3-8 below.

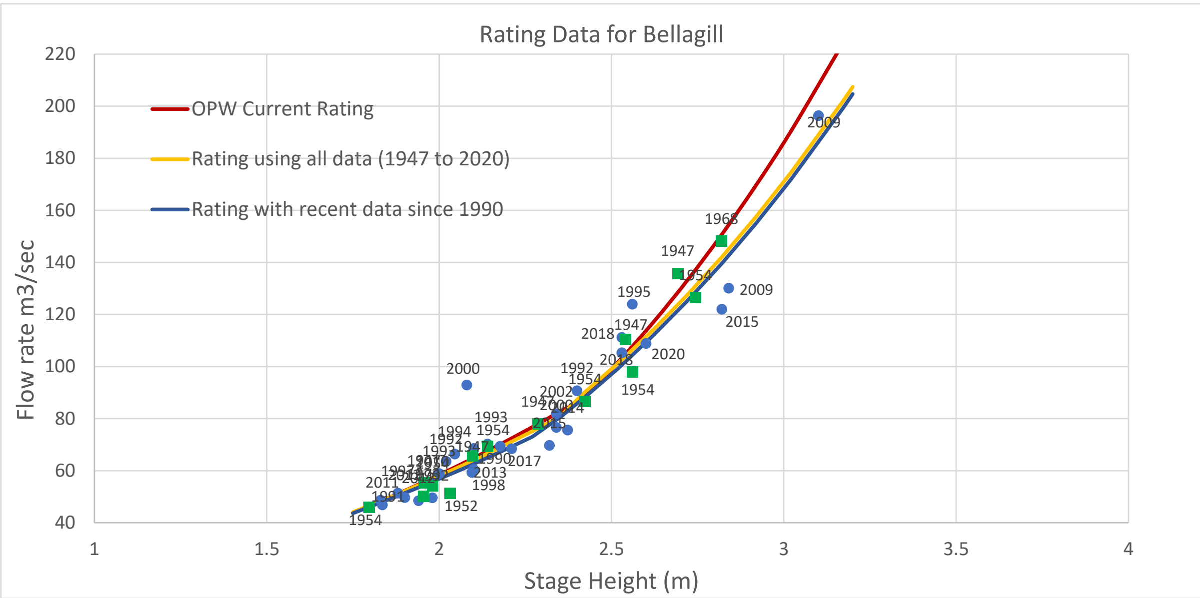

Figure 3-8 Comparison of curve fitting using all data and post 1990 data and the existing OPW Rating included for comparison

Curve fitting found that two segments of a Power Law curve fitted well the flood range. This was initially fitted by least-squares best fit. Slight adjustment to this fitted curve was carried out to force the fit through the highest observed rating of 196.4cumec at 3.1m Stage. The relationship is presented in Figure 3-9 below. To assist the flood rating review of the Bellagill station, hydraulic modelling of the Suck River was carried out over the complete flood range from 60 to 250cumec. Given the proximity of Bellagill to the flood Relief Scheme area the full hydraulic 1D/2D model for the Ballinasloe flood relief scheme was used to assist this rating review modelling exercise.

Additional survey cross-sections carried out by Murphy Surveys Ltd. in 2020 were included in the hydraulic model and merged with the CFRAM survey data set. There were no topographical issues identified between the two surveys with both surveys found to be compatible, except for the gauge datum (8.4cm difference).

The river bed at Bellagill consists mainly of sand, silt and gravel with peat (typical n=0.035), with reed growth in some locations (typical n=0.06). Bank and floodplain type varies widely from road (typical n = 0.02) to dense woodland (typical n = 0.10). However, the significant majority of the floodplain can be designated as bog (0.030), pasture (0.035) or dense woodland (0.10). For this rating review, the hydraulic modelling found that the best fit to the observed rating data was achieved by using a Manning n of 0.04 for the river channel and manning's n of 0.076 for the over banks, refer to Figure 3-10. Included in this figure is the sensitivity of the Rating relationship to floodplain roughness with the Overbank increased and decreased by 10 and 20%, respectively. The hydraulic modelling indicates a relatively small Hysteresis effect between the rising limb and the falling limb at the c. 5% at the 200cumec flow based on modelling the Nov 2009 flood event. The modelling results indicate a jump in rating where the flow is just breaking out of bank, and within bank at stage height range 40.1 to 40.2m OD which may be due to natural hysteresis effects and numerical effects from spilling from the 1D channel to the 2D flood plain on the rising limb where the flood plain is empty and on the falling limb the floodplain is already filled and is emptying even though flood levels have retreated back to channel flow.

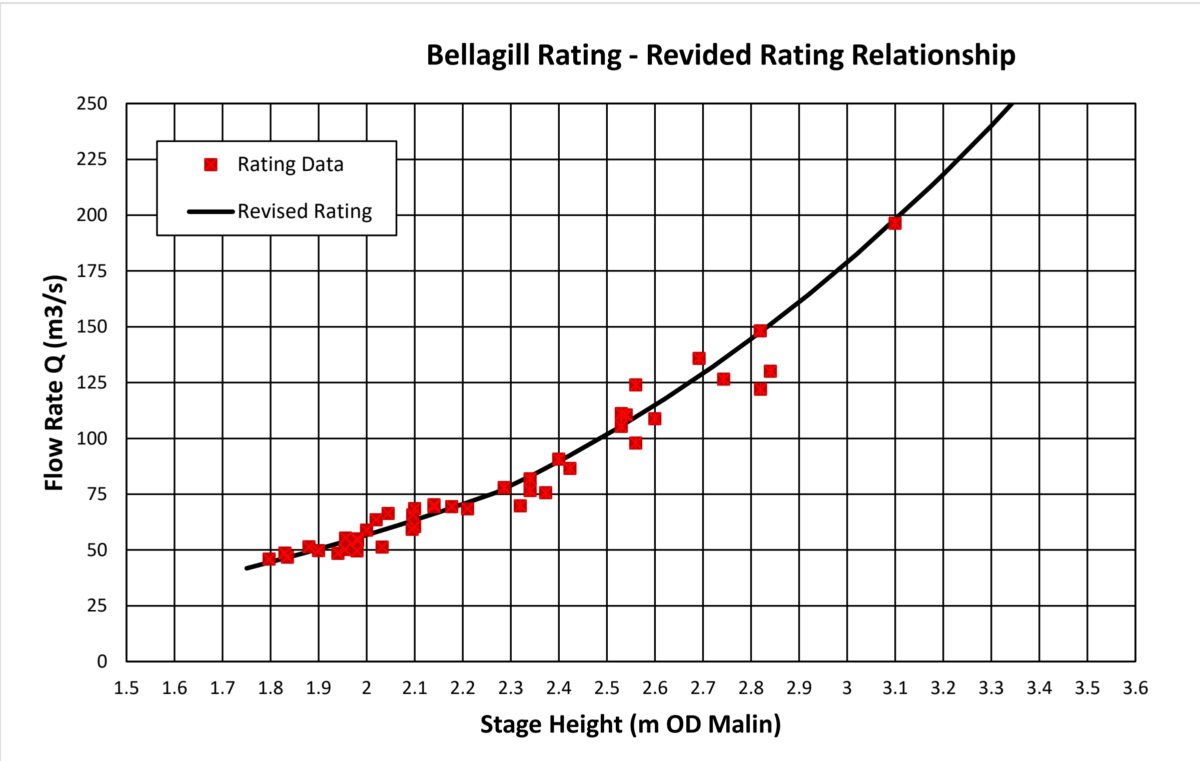

Figure 3-9 Revised Flood Rating Relationship for Bellagill gauge

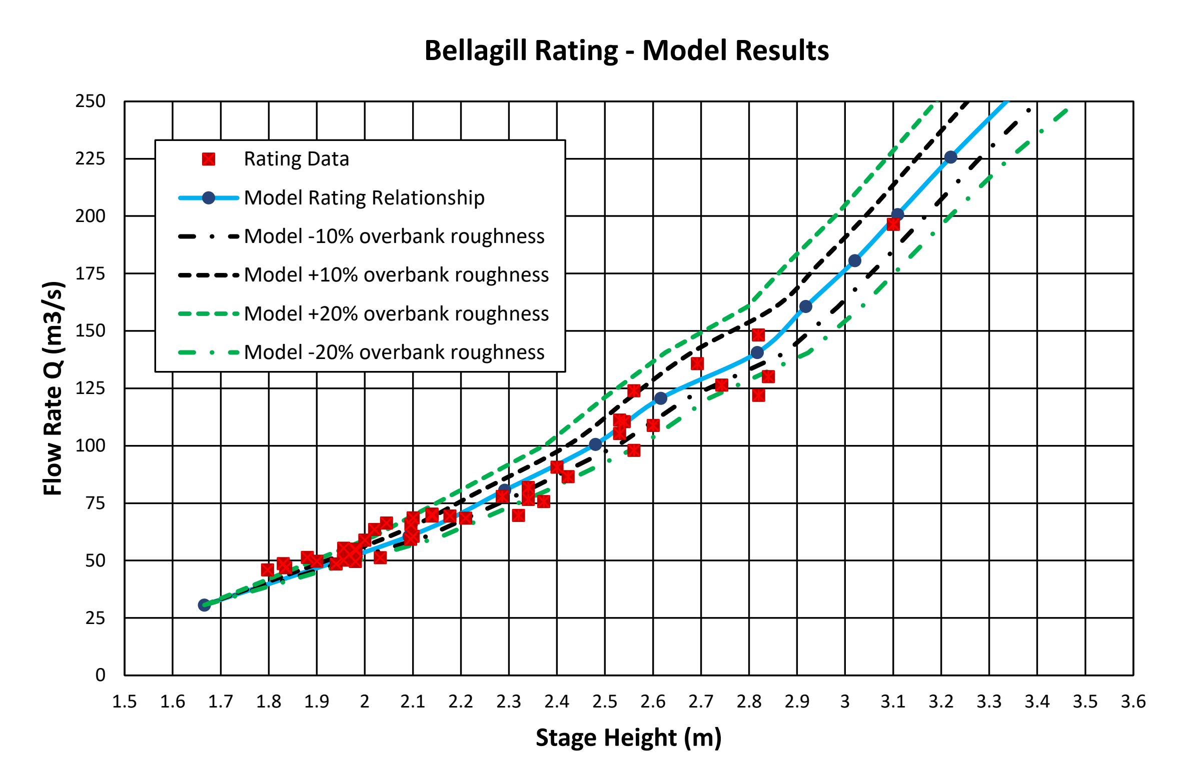

Figure 3-10 Modelled Rating Curve for Bellagill with the effect of changes to overbank roughness

It is also confirmed by the hydraulic modelling and survey work that no bypassing of the gauged channel reach section located a short distance downstream of Bellagill Bridge is bypassed with all river flows passing through the Bridge openings and therefore accounted for in the rating relationship.

The recommended revised flood flow rating equation for Bellagill to be used by this study is as follows:

$Q = 11.6*(H)^{2.29}$ for H <= 2.281m
$Q = 6.0*(H)^{3.09}$ for H > 2.281m < H < 3.19m

Where, H is the Stage Height m above staff zero and the staff zero is recorded by OPW to be 40.12m Poolbeg.

At the historical maximum recorded stage height of 3.172m on the 21st of November 2009, the estimated flow rate is 212.5cumec. This represents a reduction over the existing OPW rating relationship of 5.1% (from 224 to 212.5cumec). Based on the floodplain roughness and the degree of scatter of measurement error and the potential hysteresis effect from the downstream flood plain the uncertainty in the flood rating relationship is likely to be of the order of ± 10%, which is within the acceptable range for flood flow estimation of an A1 station.

Plate 3-1 **Gauging Station Tower and staff board located a short distance downstream of Bellagill Bridge.**

Plate 3-2 **Bellagill Bridge downstream face located c. 20m upstream of the gauging station**

3.3.3 Rating Review Derrycahill (26005)

Derrycahill hydrometric gauging station on the River Suck was established by the OPW in the early 1950s. The recorder is located at the downstream face of a steel bridge at the left (eastern) bank side. This steel bridge is supported on three masonry in-stream piers and masonry abutments that are located at the river's edge, refer to Plate 3-3. The channel invert at the gauge site is c. 39.6m OD (with the talweg depth at 39.11m OD). The typical soffit level of the bridge is 42.45m OD. The channel is reasonably regular, typically 35m wide and of the local very mild longitudinal slope. The channel is prone to weed growth, particularly on the right-hand side both upstream and downstream of the bridge; refer to Plate 3-5 and Plate 3-6.

Flow measurements for the site provided for this review date back to February 1946 up to March 2020 and flows above 41m OD are presented below in Figure 3-11. This presents considerable scatter in the rating relationship for the site, particularly at the lower flood flows which may be due to weed growth and hysteresis effects. It should be noted on the 21st of November 2009 the maximum recorded flood level of the entire AM series reached 43.2m OD which is 0.75m above the soffit of the bridge and would have submerged the bridge by a depth of 0.35m. This would not have caused overtopping of the bridge deck.

The maximum flow rating measurement is for a flood flow of 104.4cumec at a stage height of 42.4m OD (i.e. almost at the bridge soffit level). This represents approximately a 4year return period flood event based on the AM flood level series. The ratio of HGF to QMED is only 1.17, which is not very large and compounded by the high degree of scatter in the rating measurements. The extrapolation of the rating curve has an associated high degree of uncertainty in estimating the larger flood flows.

Figure 3-12 presents the current OPW flood rating relationship for the station represented by a power-law equation with two distinct periods of relationship.

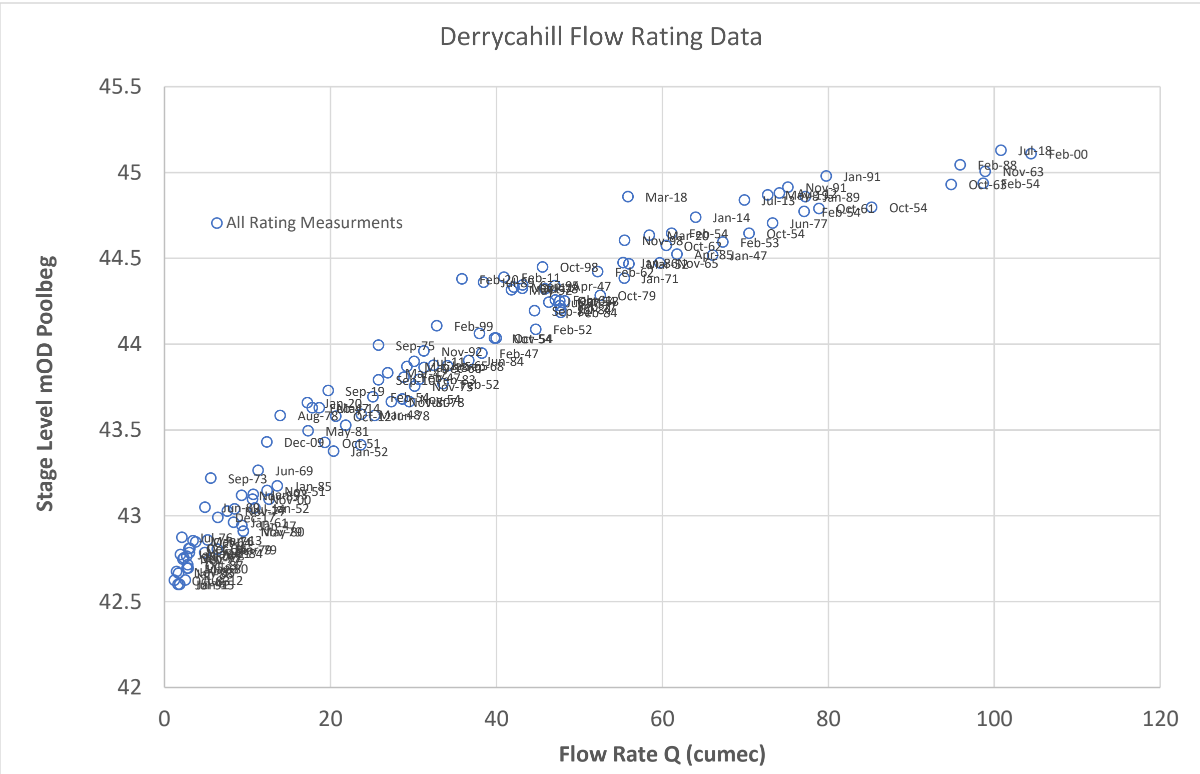

Figure 3-11 Flow Rating measurements for the Derrycahill hydrometric station

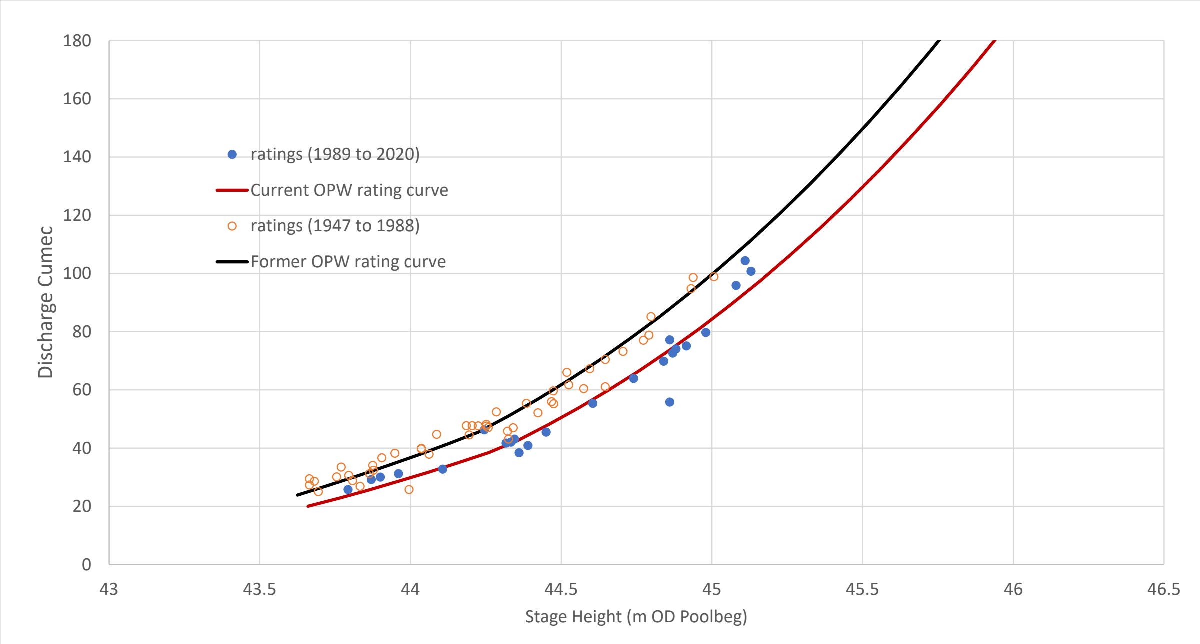

Figure 3-12 OPW Flood Rating relationship for Derrycahill Station

As part of the CFRAM study carried out by Jacob's for the Shannon Basin, including the Suck River a rating review was carried out. This review retained the current OPW ratings at Derrycahill, refer to Figure 3-13 which was extracted from the CFRAM Upper Shannon Hydrology Report (Jacobs, 2016). The CFRAM hydraulic modelling showed a slightly more efficient rating relationship having generally smaller stage producing bigger flows over the OPW rating up to 150cumec. However, examination of Figure 3-13 indicates that the modelling does not represent well the middle range of the data or the OPW current rating relationship, nor has it accounted for the two distinct rating periods in the data.

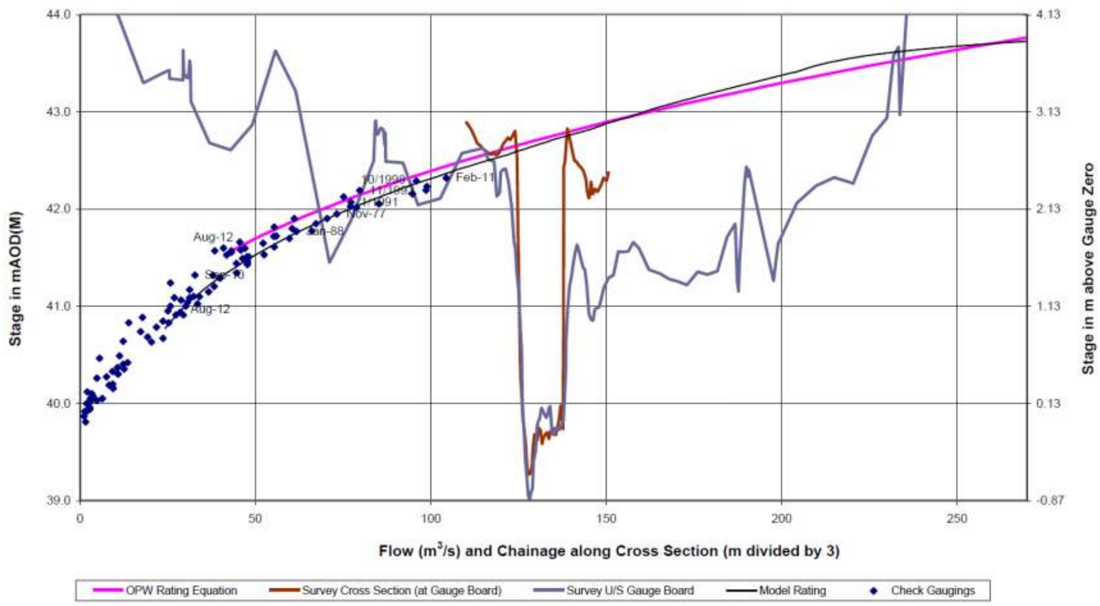

Figure 3-13 CFRAM Study Rating Review of Derrycahill Station (26005) with modelled rating

In fact, the CFRAM review of this gauge did not take into account the two distinct rating periods (1947 to 1988 and 1989 to 2020).

A hydraulic model using HECRAS was developed and the channel geometry and floodplain specified from combining a recent channel floodplain survey carried out by Murphy Survey's in 2020 with the previous CFRAM survey carried out in 2011. The modelled reach was 4.1km in length represented by a total of 21 surveyed cross-sections to define the computational reach. The river channel talweg elevation rises in the downstream direction and the recorded flood levels and model flood simulation results indicate that the channel is significantly backwatered, with little or no hydraulic gradient, refer to Figure 3-14. Such conditions make the hydraulic modelling extremely sensitive to the specification of the downstream water level boundary condition. Through trial and error, this was specified as a normal depth boundary with a very gentle hydraulic gradient of 1 in 40,000 in order to achieve the observed flood levels at the gauge from the rating measurements. To achieve the rating relationships for the two distinct rating periods (1947 to 1988 and 1989 to 2020) presented in Figure 3-15**,** moderately high Manning's roughness coefficients of 0.05 and 0.06 had to be specified in the model for those periods respectively.

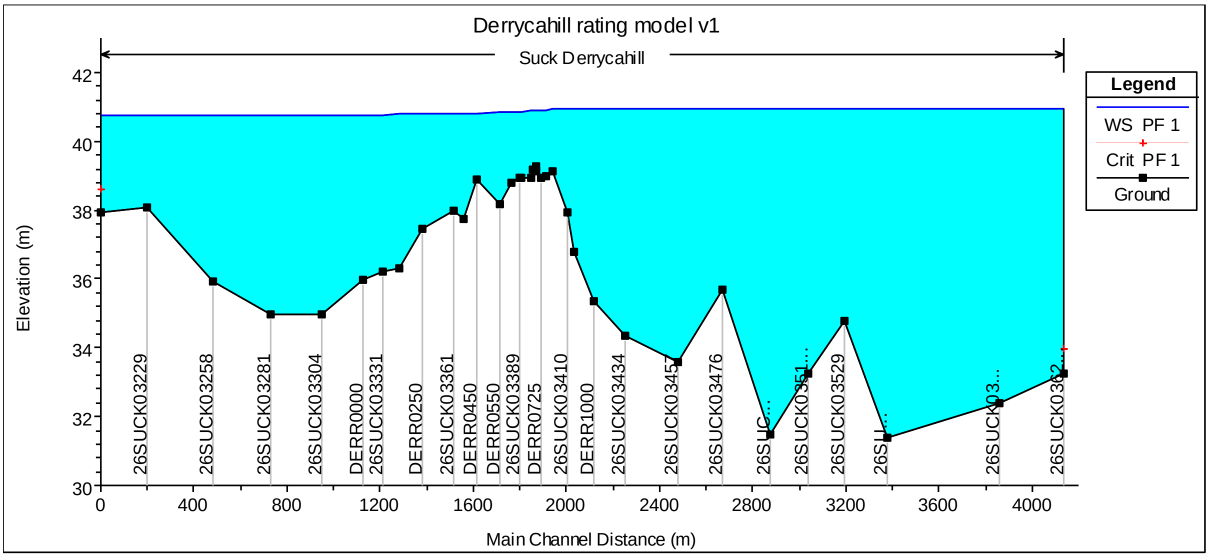

Figure 3-14 Longitudinal Flood profile at the Median Flood flow (with the river bed talweg rising in the downstream direction (towards chainage 0)

Unfortunately, this modelling is not very robust in terms of model certainty as a result of the very backwatered conditions at the gauge site and the dominance of boundary condition effects and therefore does not provide any useful assistance in extrapolating beyond what has been measured. Changing the channel roughness from 0.045 to 0.055 achieves the change noticed in the rating measurements pre and post 1989. This alteration in the specified channel roughness is reasonable as the likely effect is due to increased vegetation growth and deposition in the channel reach over time, as is evidenced from the site visit and the standing reed vegetation along the western half of the channel both upstream and downstream from Derrycahill Bridge (refer to Plate 3-5 and Plate 3-6).

In conclusion, no changes to the Derrycahill flood rating relationship are proposed at present, either for the pre-1989 OPW rating or the current OPW Rating. The reliability of the rating relationship is considered good for the QMED estimate but at the larger flood events (10years and above) is considered to be potentially unreliable. This is due to a lack of any high flood flow rating measurements and the inability to model the relationship with any degree of certainty, due primarily to the downstream channel backwatered conditions.

Overtopping of the Derrycahill bridge and the approach roads on both river banks will occur at the more extreme stage heights. They may lead to some bypassing of the gauge site but would not be considered a significant effect with almost standing water conditions generated at such high flow stages.

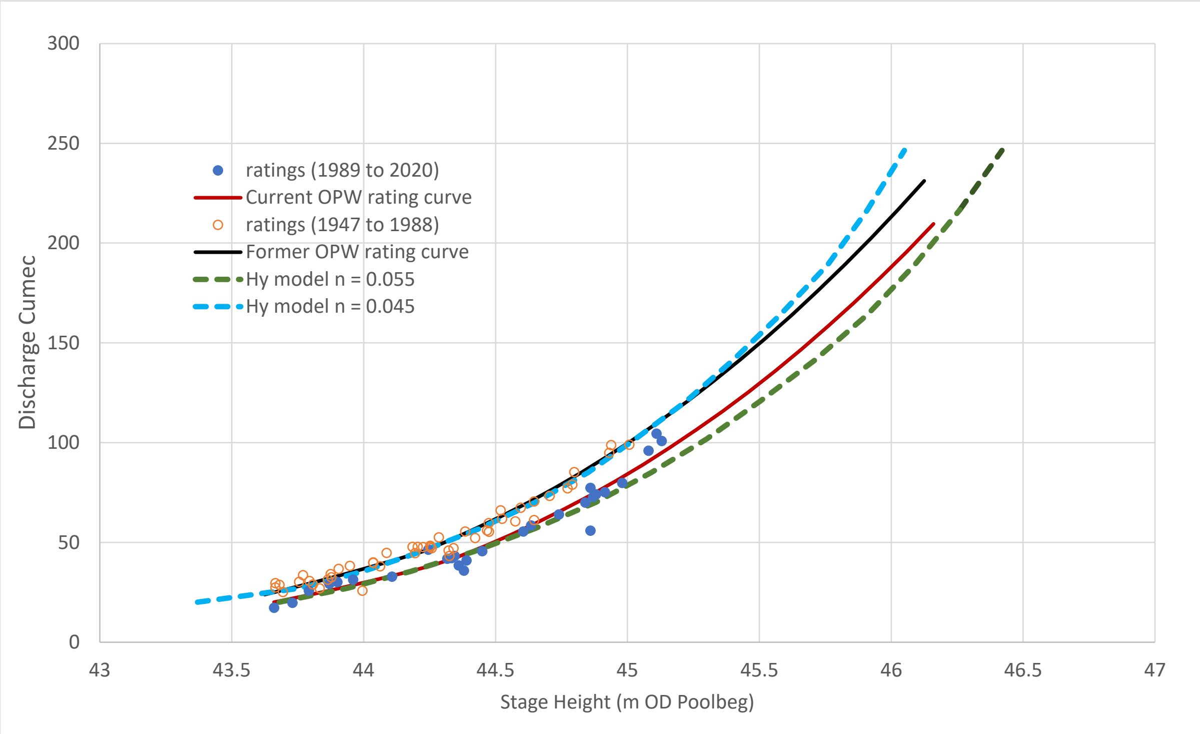

Figure 3-15 Rating Relationships from hydraulic modelling fitted by varying the Manning roughness n to fit the two sets of ratings (1947 to 1988) and (1989 to 2020)

The OPW flood rating for Derrycahill as presented in Figure 3-12 is as follows:

(1954 to 1988) $Q = 4.8*(H + 0.7)^{2.7}$ for stage height H >1.592

(1989 to 2020) $Q = 4.8*(H + 0.55)^{2.7}$ for stage height H >1.655

Staff Zero Valid from	Value [m AOD]	Height system
26/11/1939 00:00	42.61	Poolbeg
18/05/1962 00:00	42.65	Poolbeg
23/09/1976 00:00	42.63	Poolbeg
21/02/1984 00:00	42.66	Poolbeg
12/12/1989 00:00	42.66	Poolbeg

Staff zero conversion to Malin head datum based on the recent topographic survey by Murphy surveyor's gives a Staff Zero of 39.848m OD Malin02 whereas the OPW have the Staff Zero to Poolbeg datum at 42.66m OD Poolbeg (a conversion from Poolbeg to Malin of -2.812m).

A note of caution concerning the use of the current OPW flood rating is that there is a strong possibility at the higher flood stages for the channel and floodplain flow conveyance to become more efficient and thus the potential for the current rating to under estimate flood flow magnitudes with the relationship becoming more akin to previous pre-1989 rating (estimating higher flow rates for a given flood elevation).

There is some evidence of this occurring in relation to the more recent larger ratings at around 95 to 105 cumec, which on examination suggests that the current rating underpredicts such flows; refer back to either Figure 3-12 or Figure 3-15. Such an underestimation of the larger floods would result in a lower at-site flood growth curve. Higher flood flow measurements are required before reliable A1 or A2 rating classification can be achieved for this Station. The AM flow series can be used for flood growth curve estimation but is likely to produce a potentially lower growth curve than the true growth curve.

If at the higher stage levels the channel and floodplain roughness reduces and the rating tends towards the OPW previous rating as the rating measurements may potentially be suggesting, refer to Figure 3-12 then the flows recorded for significant floods of 2009 and 2015 could potentially have been c. 11% higher, with November 2009 at 194.6cumec as opposed to 175.2cumec and December 2015 at 183cumec as opposed to 165.0cumec. There is not sufficient rating information to confirm this at present without higher flow ratings being captured and therefore it not recommended to adjust the rating relationship for the AMAX series. However this uncertainty in the rating is included for in the uncertainty and sensitivity factors presented in Section 10, with a 10% uncertainty factor recommended for measurement error.

Plate 3-3 Gauging Station Tower at Derrycahill

Plate 3-4 Derrycahill Steal Bridge and gauging station

Plate 3-5 View of weed growth in channel looking downstream from Derrycahill Bridge

Plate 3-6 View of weed growth in channel looking upstream from Derrycahill Bridge

4 Hydrological Estimation Points (HEPs)

4.1 Introduction

The hydrological estimation points are selected at key locations along the River Suck and its tributaries within the Flood Relief Scheme area and the hydraulic model domain area. The HEPs are located at the upstream model boundary nodes, at the gauging stations of Bellagill and Derrycahill, at the different confluence points throughout the modelled reach and at specific reference locations (i.e. at bridges, junctions, storm outfalls etc.).

As per the Tender Brief, the HEPs are located to include all of the following:

- Upstream boundaries of all modelled watercourses;
- Points on receiving channels upstream and downstream of the confluence of any tributary;
- Point on tributaries upstream of the confluence with the receiving channel;
- Locations as necessary to accurately represent the inflows, additional to tributaries, along the modelled watercourses;
- Other points at suitable locations as necessary to ensure that there is at least one HEP every 500 m along all modelled watercourses within the Scheme Area and at 1km spacing for the reaches outside of the Scheme Area to be protected.

The Location of the HEPs within the scheme area are presented in Figure 4-1 below. The PCDs for these HEPS are presented in Table 4-1.

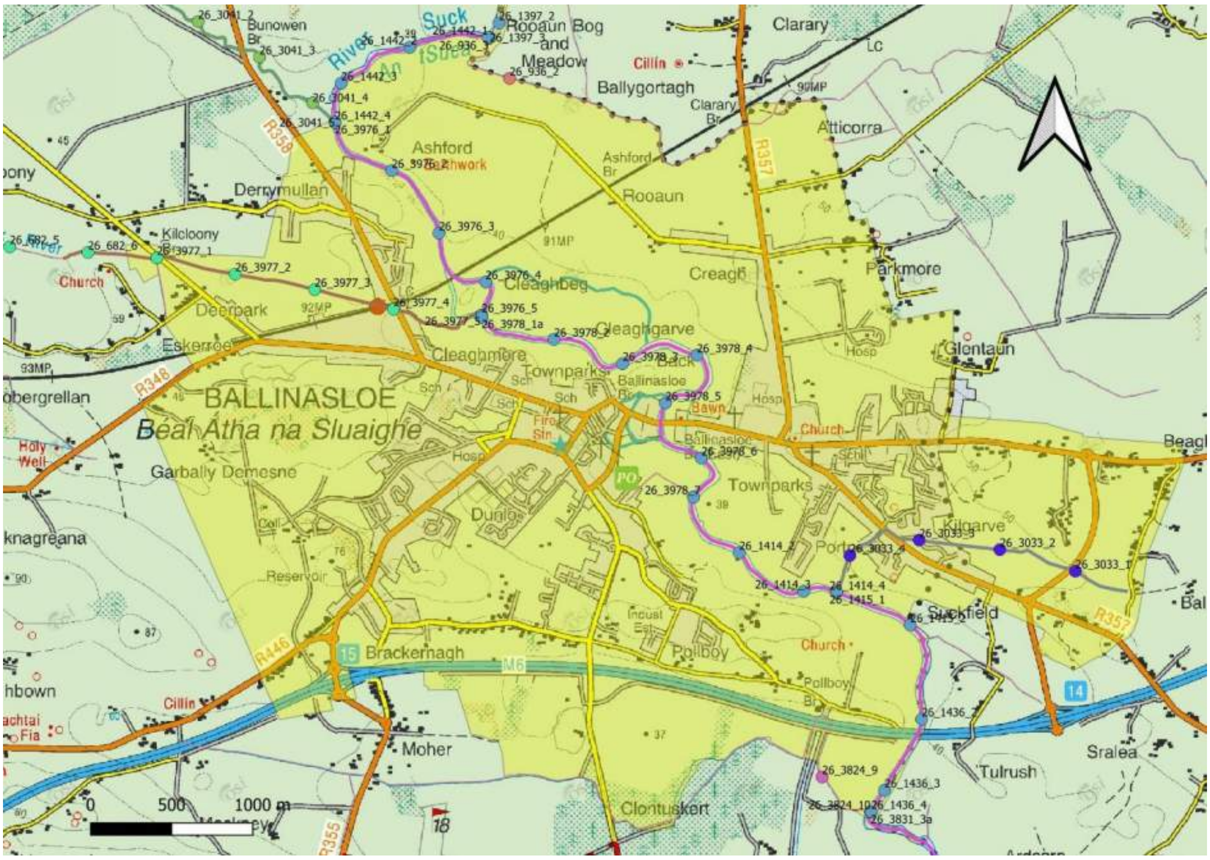

Figure 4-1 Location of primary Hydrological Estimation Points

Table 4-1 Selected HEPs included in Model and the Revised PCD values

Node Reference	Easting	Northing	water_body	node_id	cente	centn	area	saar	farl	urbext	forest	peat	Node Reference
506_hep_26_682_5	581688.8	732175.5	Deerpark	26_682_5	176560	231750	56.49	1072.6	0.993	0.0075	0.0649	0.058	506_hep_26_682_5
506_hep_26_682_6	582170.7	732140.5	Deerpark	26_682_6	176640	231750	56.93	1071.9	0.993	0.0074	0.0644	0.0575	506_hep_26_682_6
506_hep_26_682_7	582595.6	732107.5	Deerpark	26_682_7	176850	231750	57.23	1071.3	0.993	0.0074	0.0641	0.0572	506_hep_26_682_7
506_hep_26_936_2	584770.2	733213.3	Cuilleen	26_936_2	188300	232830	13.2	931.6	1	0	0.0634	0.0694	506_hep_26_936_2
506_hep_26_936_3	584641.6	733459.9	Cuilleen	26_936_3	188160	232830	13.34	932.1	1	0	0.0627	0.0686	506_hep_26_936_3
506_hep_26_1397_1	584844.2	734022.1	Suck	26_1397_1	174320	261250	1208.54	1045.5	0.983	0.0021	0.0836	0.213	506_hep_26_1397_1
506_hep_26_1397_2	584705.2	733555.2	Suck	26_1397_2	174320	260990	1209.72	1045.5	0.983	0.0021	0.0835	0.2128	506_hep_26_1397_2
506_hep_26_1397_3	584646.7	733465.3	Suck	26_1397_3	174320	260990	1209.77	1045.5	0.983	0.0021	0.0835	0.2128	506_hep_26_1397_3
506_hep_26_1419_4	584844.2	734022.1	Suck	26_1419_4	174320	261250	1208.54	1045.5	0.983	0.0021	0.0836	0.213	506_hep_26_1419_4
506_hep_26_2853_5	582447.7	733801.1	Bunowen	26_2853_5	172860	237990	132.79	1082.8	0.999	0.0043	0.0805	0.0995	506_hep_26_2853_5
506_hep_26_3041_1	582447.7	733801.1	Bunowen	26_3041_1	173300	237990	135.59	1080.7	0.999	0.0042	0.0799	0.1036	506_hep_26_3041_1
506_hep_26_3041_2	582850.6	733563.2	Bunowen	26_3041_2	173300	237990	135.94	1080.4	0.999	0.0042	0.0797	0.1037	506_hep_26_3041_2
506_hep_26_3041_3	583228.5	733344.2	Bunowen	26_3041_3	173400	237990	136.32	1080.2	0.999	0.0042	0.0795	0.1044	506_hep_26_3041_3
506_hep_26_3041_4	583556.4	733062.3	Bunowen	26_3041_4	173540	237990	136.66	1079.9	0.999	0.0042	0.0793	0.1044	506_hep_26_3041_4
506_hep_26_3041_5	583693.8	732941.9	Bunowen	26_3041_5	173600	237990	136.73	1079.8	0.999	0.0042	0.0793	0.1043	506_hep_26_3041_5
506_hep_26_3977_1	582595.6	732107.5	Deerpark	26_3977_1	176850	231750	57.25	1071.3	0.993	0.0074	0.064	0.0572	506_hep_26_3977_1
506_hep_26_3977_2	583078.5	732006.5	Deerpark	26_3977_2	176980	231750	57.49	1070.8	0.993	0.0073	0.0638	0.057	506_hep_26_3977_2
506_hep_26_3977_3	583568.4	731911.5	Deerpark	26_3977_3	177560	231750	61.03	1064.6	0.994	0.011	0.066	0.0536	506_hep_26_3977_3
506_hep_26_3977_4	584054.3	731790.6	Deerpark	26_3977_4	177560	231750	61.55	1063.8	0.994	0.0155	0.0655	0.0532	506_hep_26_3977_4
506_hep_26_3977_5	584590.5	731749.6	Deerpark	26_3977_5	177740	231750	61.57	1063.8	0.994	0.0155	0.0655	0.0532	506_hep_26_3977_5
506_hep_26_3824_9	586696.7	728908.2	Loughbown	26_3824_9	184080	228850	8	962.7	1	0.0424	0.0556	0.005	506_hep_26_3824_9
506_hep_26_3824_10	586995	728692.8	Loughbown	26_3824_10	184170	228850	8.41	961.5	1	0.0403	0.0754	0.0102	506_hep_26_3824_10
506_hep_26_3033_1	588258.4	730175.9	Pollboy26	26_3033_1	189260	230880	2.1	919.7	1	0.0549	0	0.0222	506_hep_26_3033_1
506_hep_26_3033_2	587792.5	730308.9	Pollboy26	26_3033_2	189030	230880	2.43	920.1	1	0.0484	0	0.0193	506_hep_26_3033_2
506_hep_26_3033_3	587295.6	730367.8	Pollboy26	26_3033_3	188780	230880	2.63	920.3	1	0.0541	0.004	0.0177	506_hep_26_3033_3
506_hep_26_3033_4	586867.7	730272.9	Pollboy26	26_3033_4	188560	230880	2.81	920.4	1	0.0732	0.0037	0.0166	506_hep_26_3033_4
506_hep_26_3033_5	586786	730044.9	Pollboy26	26_3033_5	188550	230880	2.82	920.4	1	0.073	0.0037	0.0166	506_hep_26_3033_5
506_hep_26_1442_1	584638.1	733465.7	Suck	26_1442_1	174320	259900	1223.12	1044.2	0.983	0.002	0.0833	0.2112	506_hep_26_1442_1
506_hep_26_1442_2	584155.3	733404.2	Suck	26_1442_2	174320	259900	1223.26	1044.2	0.983	0.002	0.0833	0.2112	506_hep_26_1442_2
506_hep_26_1442_3	583732.4	733183.3	Suck	26_1442_3	174320	259900	1223.66	1044.2	0.983	0.002	0.0833	0.2111	506_hep_26_1442_3
506_hep_26_1442_4	583693.9	732942	Suck	26_1442_4	174320	259900	1223.82	1044.2	0.983	0.002	0.0832	0.2111	506_hep_26_1442_4

Table 4-1 (Continued) Selected HEPs included in Model and the Revised PCD values

Node Reference	Easting	Northing	water_body	node_id	cente	centn	area	saar	farl	urbext	forest	peat
506_hep_26_3976_1	583694	732941.5	Suck	26_3976_1	174320	259900	1361.99	1047.7	0.984	0.0023	0.0828	0.2003
506_hep_26_3976_2	584043.3	732644.4	Suck	26_3976_2	174320	259900	1362.32	1047.7	0.984	0.0023	0.0828	0.2002
506_hep_26_3976_3	584334.3	732259.5	Suck	26_3976_3	174320	259900	1362.53	1047.6	0.984	0.0023	0.0828	0.2002
506_hep_26_3976_4	584622.2	731958.5	Suck	26_3976_4	174320	259900	1362.83	1047.6	0.984	0.0024	0.0828	0.2002
506_hep_26_3976_5	584597.9	731754.9	Suck	26_3976_5	174320	259900	1362.84	1047.6	0.984	0.0024	0.0828	0.2002
506_hep_26_3978_2	585044.1	731604.6	Suck	26_3978_2	174320	257920	1425.37	1048.3	0.985	0.0029	0.082	0.1937
506_hep_26_3978_3	585467	731455.6	Suck	26_3978_3	174320	257920	1427.33	1048.1	0.985	0.0031	0.0819	0.1934
506_hep_26_3978_4	585924.9	731506.6	Suck	26_3978_4	174320	257920	1427.72	1048.1	0.985	0.0032	0.0819	0.1933
506_hep_26_3978_5	585731	731212.7	Suck	26_3978_5	174320	257920	1427.72	1048.1	0.985	0.0032	0.0819	0.1933
506_hep_26_3978_6	585952.9	730872.8	Suck	26_3978_6	174320	257920	1428.26	1048.1	0.985	0.0034	0.0818	0.1933
506_hep_26_3978_7	585903.9	730632.8	Suck	26_3978_7	174320	257920	1431.79	1047.8	0.985	0.0044	0.0816	0.1928
506_hep_26_1414_1	585903.9	730632.8	Suck	26_1414_1	174320	257920	1431.94	1047.8	0.985	0.0044	0.0816	0.1928
506_hep_26_1414_2	586185.9	730289.9	Suck	26_1414_2	174320	257920	1432.54	1047.7	0.985	0.0045	0.0816	0.1927
506_hep_26_1414_3	586583.8	730051.9	Suck	26_1414_3	174320	257920	1433.3	1047.7	0.985	0.0046	0.0815	0.1926
506_hep_26_1414_4	586785.5	730045	Suck	26_1414_4	174320	257920	1433.58	1047.6	0.985	0.0047	0.0815	0.1926
506_hep_26_1415_1	586785.6	730044.8	Suck	26_1415_1	174320	257920	1436.43	1047.4	0.985	0.0048	0.0814	0.1922
506_hep_26_1415_2	587240.6	729844	Suck	26_1415_2	174320	257920	1436.65	1047.4	0.985	0.0048	0.0814	0.1922
506_hep_26_1436_2	587310.6	729264.1	Suck	26_1436_2	174320	257920	1436.9	1047.3	0.985	0.0048	0.0813	0.1921
506_hep_26_1436_3	587081.7	728826.2	Suck	26_1436_3	174320	257920	1436.91	1047.3	0.985	0.0048	0.0813	0.1921
506_hep_26_3831_1a	586996.3	728690.6	Suck	26_3831_3a	174320	257920	1445.32	1046.8	0.9851	0.005	0.0813	0.191
506_hep_26_3831_2	587477.6	728047.3	Suck	26_3831_2	174320	257820	1447.92	1046.7	0.985	0.005	0.0815	0.1914
506_hep_26_1436_4	586998.8	728693.3	Suck	26_1436_4	174320	257920	1436.91	1047.3	0.985	0.0048	0.0813	0.1921
506_hep_26_3978_1a	584599.1	731742.4	Suck	26_3978_1a	174320	259900	1424.41	1048.3	0.984	0.003	0.0821	0.1938

Table 4-1 (Continued) Selected HEPs included in Model and the Revised PCD values

Node Reference	pasture	alluv	flatwet	saape	fai	bfisoil	netlen	stmfrq	draind	msl	s1085	tayslo	artdrain	artdrain2
506_hep_26_682_5	0.872	0.017	0.640	491.3	0.315	0.641	54.54	41	0.966	14.37	3.306	0.77	0	0
506_hep_26_682_6	0.873	0.017	0.640	491.3	0.316	0.641	55.04	41	0.967	14.87	3.263	0.682	0	0
506_hep_26_682_7	0.873	0.017	0.640	491.3	0.316	0.641	55.47	41	0.969	15.3	3.254	0.611	0	0
506_hep_26_936_2	0.728	0.000	0.640	488.4	0.303	0.609	16.57	15	1.256	7.92	3.472	1.024	0	0
506_hep_26_936_3	0.730	0.004	0.640	488.4	0.307	0.609	17.1	15	1.282	8.44	3.196	0.942	0	0
506_hep_26_1397_1	0.689	0.026	0.680	466.4	0.168	0.651	908.89	763	0.752	108.58	0.408	0.133	0.0003	0
506_hep_26_1397_2	0.690	0.026	0.680	466.4	0.168	0.650	909.39	763	0.752	109.08	0.415	0.131	0.0003	0
506_hep_26_1397_3	0.690	0.026	0.680	466.4	0.168	0.650	909.52	763	0.752	109.2	0.415	0.132	0.0003	0
506_hep_26_1419_4	0.689	0.026	0.680	466.4	0.168	0.651	908.56	761	0.752	108.58	0.408	0.133	0.0003	0
506_hep_26_2853_5	0.800	0.009	0.650	486.7	0.201	0.628	97.6	75	0.735	30.78	1.891	0.48	0	0
506_hep_26_3041_1	0.796	0.009	0.650	486.7	0.202	0.628	98.88	77	0.729	30.78	1.891	0.48	0	0
506_hep_26_3041_2	0.795	0.009	0.650	486.7	0.204	0.628	99.38	77	0.731	31.28	2.066	0.451	0	0
506_hep_26_3041_3	0.793	0.009	0.650	486.7	0.205	0.628	99.88	77	0.733	31.78	2.055	0.448	0	0
506_hep_26_3041_4	0.792	0.009	0.650	486.7	0.206	0.628	100.38	77	0.735	32.28	2.045	0.422	0	0
506_hep_26_3041_5	0.792	0.009	0.650	486.8	0.207	0.628	100.56	77	0.736	32.47	2.04	0.422	0	0
506_hep_26_3977_1	0.873	0.017	0.640	491.3	0.316	0.641	55.86	43	0.976	15.3	3.254	0.611	0	0
506_hep_26_3977_2	0.874	0.017	0.640	491.3	0.317	0.641	56.36	43	0.98	15.8	3.12	0.725	0	0
506_hep_26_3977_3	0.877	0.016	0.640	491.3	0.302	0.642	56.86	43	0.932	16.3	3.03	0.559	0	0
506_hep_26_3977_4	0.874	0.016	0.640	491.3	0.307	0.642	57.36	43	0.932	16.8	2.928	0.664	0	0
506_hep_26_3977_5	0.873	0.016	0.640	491.3	0.307	0.642	57.96	43	0.941	17.4	2.777	0.685	0	0
506_hep_26_3824_9	0.735	0.017	0.640	492.2	0.256	0.737	5.55	3	0.694	5.07	3.359	0.699	0	0
506_hep_26_3824_10	0.719	0.029	0.640	492.2	0.265	0.738	5.96	3	0.709	5.48	3.398	0.7	0	0
506_hep_26_3033_1	0.913	0.000	0.640	490.0	0.001	0.691	0.34	1	0.163	0.34	14.605	12.796	0	0
506_hep_26_3033_2	0.924	0.000	0.640	490.2	0.028	0.691	0.84	1	0.347	0.84	7.828	0.331	0	0
506_hep_26_3033_3	0.921	0.000	0.640	490.3	0.057	0.699	1.34	1	0.51	1.34	4.48	2.288	0	0
506_hep_26_3033_4	0.903	0.000	0.640	490.4	0.080	0.713	1.84	1	0.656	1.85	4.807	3.1	0	0
506_hep_26_3033_5	0.903	0.000	0.640	490.4	0.082	0.713	2.09	1	0.741	2.09	5.307	3.644	0	0
506_hep_26_1442_1	0.690	0.026	0.680	466.7	0.169	0.641	926.62	779	0.758	109.2	0.401	0.132	0.0003	0
506_hep_26_1442_2	0.690	0.026	0.680	466.7	0.169	0.641	927.12	779	0.758	109.7	0.401	0.132	0.0003	0
506_hep_26_1442_3	0.690	0.026	0.680	466.7	0.170	0.641	927.62	779	0.758	110.2	0.401	0.132	0.0003	0
506_hep_26_1442_4	0.690	0.026	0.680	466.7	0.170	0.641	927.87	779	0.758	110.45	0.4	0.132	0.0003	0

Table 4-1 (Continued) Selected HEPs included in Model and the Revised PCD values

Node Reference	pasture	alluv	flatwet	saape	fai	bfisoil	netlen	stmfrq	draind	msl	s1085	tayslo	artdrain	artdrain2
506_hep_26_3976_1	0.700	0.024	0.670	468.7	0.174	0.596	1028.4	857	0.755	110.45	0.396	0.132	0.0002	0
506_hep_26_3976_2	0.700	0.024	0.670	468.7	0.174	0.596	1028.9	857	0.755	110.95	0.399	0.132	0.0002	0
506_hep_26_3976_3	0.700	0.024	0.670	468.7	0.174	0.596	1029.4	857	0.756	111.45	0.399	0.132	0.0002	0
506_hep_26_3976_4	0.700	0.024	0.670	468.7	0.174	0.596	1029.9	857	0.756	111.95	0.4	0.131	0.0002	0
506_hep_26_3976_5	0.700	0.024	0.670	468.7	0.174	0.596	1030.2	857	0.756	112.19	0.4	0.132	0.0002	0
506_hep_26_3978_2	0.708	0.024	0.670	469.7	0.180	0.596	1088.6	901	0.764	112.69	0.403	0.132	0.0002	0
506_hep_26_3978_3	0.708	0.024	0.670	469.7	0.180	0.596	1089.1	901	0.763	113.19	0.383	0.133	0.0002	0
506_hep_26_3978_4	0.708	0.025	0.670	469.7	0.180	0.596	1089.6	901	0.763	113.69	0.369	0.133	0.0002	0
506_hep_26_3978_5	0.708	0.025	0.670	469.7	0.180	0.596	1090.1	901	0.764	114.19	0.362	0.131	0.0002	0
506_hep_26_3978_6	0.708	0.025	0.670	469.8	0.181	0.596	1090.6	901	0.764	114.69	0.395	0.134	0.0002	0
506_hep_26_3978_7	0.707	0.025	0.670	469.8	0.180	0.596	1091	901	0.762	115.02	0.385	0.135	0.0002	0
506_hep_26_1414_1	0.707	0.025	0.670	469.8	0.180	0.596	1091.5	903	0.762	115.02	0.385	0.135	0.0002	0
506_hep_26_1414_2	0.707	0.025	0.670	469.8	0.180	0.596	1092	903	0.762	115.52	0.383	0.133	0.0002	0
506_hep_26_1414_3	0.707	0.025	0.670	469.8	0.180	0.596	1092.5	903	0.762	116.02	0.383	0.131	0.0002	0
506_hep_26_1414_4	0.707	0.025	0.670	469.8	0.181	0.596	1092.7	903	0.762	116.23	0.382	0.132	0.0002	0
506_hep_26_1415_1	0.708	0.025	0.670	469.9	0.180	0.596	1094.8	905	0.762	116.23	0.382	0.132	0.0002	0
506_hep_26_1415_2	0.708	0.025	0.670	469.9	0.180	0.596	1095.3	905	0.762	116.73	0.382	0.133	0.0002	0
506_hep_26_1436_2	0.708	0.025	0.670	469.9	0.181	0.596	1096.8	907	0.763	117.35	0.382	0.131	0.0002	0
506_hep_26_1436_3	0.708	0.025	0.670	469.9	0.181	0.596	1097.3	907	0.764	117.85	0.392	0.132	0.0002	0
506_hep_26_3831_1a	0.708	0.025	0.670	470.0	0.181	0.597	1103.4	910	0.763	118.05	0.398	0.132	0.0002	0
506_hep_26_3831_2	0.707	0.025	0.670	470.1	0.181	0.596	1104.6	913	0.763	118.96	0.401	0.133	0.0002	0
506_hep_26_1436_4	0.708	0.025	0.670	469.9	0.181	0.596	1097.4	907	0.764	118.01	0.398	0.132	0.0002	0
506_hep_26_3978_1a	0.708	0.024	0.669	469.7	0.180	0.598	1088.1	900	0.764	112.22	0.4	0.132	0.0002	0

5 Flood Flow Estimation

5.1 Introduction

Gauged and ungauged statistical methods are used to estimate the return period flood flow magnitudes in the River Suck and its tributaries at Ballinasloe. These estimates are required at the various HEP's nodes within the Ballinasloe Flood Relief Scheme hydraulic model area.

5.2 Flood Estimation Methodology

The general approach for conducting flood frequency analysis both in Ireland and the UK is based on the index flood method, using the median of the annual maximum flood as the index flood. For a given subject site, a region-of-influence approach is used, involving the creation of a collection of either hydrologically or geographically similar catchments that comprise the pooling group from which a flood growth curve can be developed. The index flood magnitude, when multiplied by the flood growth curve factor, produces the return period flood flow estimate.

5.2.1 Gauged Sites

In some cases, a subject site may coincide with or be close to a gauging station location for which a measured flood flow series over a sufficient number of years provides a reliable flood flow series for statistical frequency analysis. In reality, the majority of subject sites are unlikely to coincide with or near a gauging station, and consequently, such sites are referred to as ungauged sites.

At a gauged site, a probability distribution is fitted to the flood series with the assumption that the flood series is stationary, random and homogenous (i.e. random sample extracted from a single parent population of events). Single site analysis involves selecting a suitable probability distribution (such as a Gumbel or Weibull or other such extreme probability distributions) and either graphically or numerically fitting the selected distribution to the flood series. Generally, the distribution fitting is carried out through the use of either plotting positions and least square fit methods or numerical methods such as the ordinary method of moments, probability weighted moments, l-moments and maximum likelihood methods.

The statistical analysis for a gauged site may use a single-site distribution from the gauged site itself or may use a pooled analysis from suitable donor gauged sites or a combination of both to produce a flood growth curve from which to estimate the specific flood quantile Q_T. The latter using donor sites represents a pooled analysis, which is the recommended method by the OPW Irish Flood Studies Update method (FSU). The flood data from several gauged river sites are in effect pooled together to provide a statistically more reliable estimate of the required flood quantile, particularly for the larger return periods as it represents a larger sample for the population of events and reduces the dependance on a single gauge site which may or may not well represent the gauged site and on the potential for measurement and sample error at that site.

The pooling group of gauged stations is selected based on similarity both regionally and in their physical catchment descriptors such as catchment area, annual rainfall and soils and geology conditions, catchment and channel slope, etc. to the subject site. This pooling allows through the use of the index flood method a statistically more reliable and robust flood quantile estimate over the single site growth curve.

$$Q_T = Q_{index} * X_T \qquad (1)$$

Where, Q_T is the T-year flood quantile, Q_{index} is the index flood (FSU and FEH recommend the median flood QMED) obtained from the gauged site annual maximum or POT flood series and X_T is the dimensionless flood growth curve obtained from the pooled analysis.

The general requirement for a pooling group in respect to estimating the return period flood flow quantile Q_T is that the group of selected stations provide at least 5T AM station years (e.g. 100year return period requires 500 station years). If too few stations are included the precision of the Q_T estimate is sacrificed, but if far too many stations are selected the assumption of homogeneity from a single representative parent of floods may be compromised. At the larger return periods such as 500 and 1000 year, the 5T requirement becomes unfeasible as a 1000year return period estimate would, under this rule, require 5000station years which is almost the entire available AM flood series and gauging stations for Ireland and as such would certainly compromise the homogeneity assumption.

Single-site analysis, either independent or in combination with pooled analysis, is acceptable where the gauge is reliable and the AM series is reasonably long. As a guide, such single-site analysis for estimating design flood flows can be applied where the record length would typically exceed 0.5T (i.e. a 50year record length for estimating the 100year flood).

A drawback with the pooled regional analysis for Ireland is that to achieve the 5T station years quite a number of gauging stations may be required, many of which may not be within the catchment or even the region and may not be as hydrologically similar to the subject site as desired, which is not consistent with the homogeneity assumption of originating from a single parent distribution. This can give rise to considerable scatter of the pooling group flood distribution characteristics (i.e. coefficient of variation, coefficient skewness and Kurtosis) and producing an average of the growth curve that may not be consistent with the gauged information if available near the site.

5.2.2 Ungauged sites

Ungauged sites are all sites not located within close proximity to a reliable gauged site. The estimation of the flood quantiles depends completely on extrapolating from gauged donor sites both in respect to estimating the index flood quantile QMED and the flood growth curve X_T.

The standard method is to use an estimation equation that was calibrated by multiple regression analysis, which gives a relationship between the QMED and physical catchment descriptors (previously referred to in the FSR as catchment characteristic parameters). The normal approach for ungauged sites is the use of index flood with a pooled or regional growth curve. The procedure in estimating the index flood (i.e. the median flood QMED or the mean annual maximum flood QBAR) involves deriving it from either a suitable donor or analog gauged site or use of an empirical flood estimation equation.

A donor site is considered to be a gauging station site on the same river as the subject site and can be either upstream or downstream. An analog site is considered to be a gauged site not on the same river as the subject site, including being on another tributary within the same parent catchment. It is assumed that an analog site is chosen so that it is hydrologically similar (i.e. catchment descriptors are similar).

The empirical flood estimation equations available are the FSU QMED equation for physical catchment descriptors (PCDs), the IH124 QBAR equation for small ungauged catchments (<25km^2) or the original Flood Study Report (1975) QBAR catchment characteristic equation. The latter FSR QBAR method is generally considered redundant being replaced by better resolution FSU QMED method in respect to catchment descriptor mapping and also associated with more extensivr gauged flood data (increase number of stations and years available to the FSU method over the FSR method (i.e. AM series up to 2005 for the FSU and only up to 1974 for the FSR).

5.2.3 Annual Maxima Series

In Ireland, flood frequency analysis is generally carried out on the Annual Maxima (AM) series of gauged flows. This represents a series of maximum flows that are extracted from the gauge record for each hydrological year (1st October to 30th September). Such flood frequency analysis can also be applied to the Peaks Over Threshold (POT) series of independent flood events, whose peak exceeds a minimum threshold value. This series can allow a number of additional flood events that exceed the threshold value in a given hydrometric year over an AM series. The POT flood analysis is the preferred method in the UK and in the UK FEH (1998) method and for smaller records and smaller flashier catchments provides more sampling of floods.

For Ireland and particularly for the larger winter flooding catchments, where generally the river receives only one large independent flood per year and the record series is reasonable long in term of years, the AM series approach is considered to be sufficient. In flashy catchments where flooding is irregular or where the record length is short, a POT frequency analysis is likely to be more reliable as a greater sampling of floods and ensures all floods above the threshold are retained and also filters the low flood magnitudes below the threshold and thus eliminating some dry flood years from the series. The selection of an appropriate threshold value is important and often requires a sensitivity analysis to be performed on different thresholds values. For the Suck River the AM series approach is considered suitable.

5.2.4 Flood Frequency Distributions

There are numerous statistical distributions available and in use today for flood analysis. The distribution varies in complexity and shape from two parameters to multiple parameter equations that are based on the statistical moments of the distribution. The common distributions used in Ireland and the UK and in the FSU and FEH methods are presented below in Table 5-1.

Table 5-1 Probability Distributions included in the flood frequency Analysis

Distribution name	parameters
EV1 Extreme Valve Type 1 (EV1 or also known as Gumbel), a	2 parameter location and scale the Skewness of this distribution is set at 1.14
GEV General Extreme Value type distribution (which depending on the skewness may also be known as EV2 or EV3	3 parameter location, scale and shape parameter
LO Logistic Distribution	2 parameter location and scale (skewness is 0)
GLO General Logistic Distribution	3 parameter location, scale and shape parameter
LN2 Log Normal	2 parameter location and scale (of the logarithm of the AM series is 0)

Distribution name	parameters
LN3 Log Normal 3	3 parameter distribution of the log series having location, scale and shape parameters
LP3 Log Pearson Type 3	3 parameter distribution of the log series having location, scale and shape parameters
Weibull Distribution	3 parameter distribution having location, scale and shape parameters

5.2.5 Fitting of statistical distributions

Different statistical methods are available for fitting these distributions to the flood series with the most common methods using either plotting position and least-squares fit, ordinary method of moments, probability weighted moments and L-moment methods or maximum likelihood methods. The L-moments based on Hosting (1986, 1990) and Hosking and Wallis (1997) are generally the preferred methods in Ireland and used in the FSU (2009) and consequently was applied to this study to fit the above distributions to annual maximum flood flow series at the selected gauges. The L-moment method suffers less from the effects of sampling variability and is generally more robust to outliers within the sample than the other conventional methods.

5.2.6 Estimation of Flood Quantiles

The L-moments produce a location parameter u, a scale parameter α and a shape parameter k. These parameters are inputted to specifically derived equations for the particular distribution along with the non-exceedance probability F.

$$F = 1 - \frac{1}{T} \qquad (2)$$

GEV $$Q_T = u + \alpha(1 - (-LN(F))^k)/k \qquad (3)$$

EV1 $$Q_T = u - \alpha LN(-LN(F)) \qquad (4)$$

LO $$Q_T = u + \alpha LN\left(\frac{F}{1-F}\right) \qquad (5)$$

GLO $$Q_T = u + \alpha\left(1 - \left(\frac{1-F}{F}\right)^k\right)/k \qquad (6)$$

Refer to papers by Hosting (1986, 1990) and Hosking and Wallis (1997) for the l-moment expressions applicable to the above distributions. All of the distributions set out in Table 5-1 were considered in this study.

5.3 Flood Frequency Analysis of the River Suck Gauges

5.3.1 At Site Analysis

The River Suck has four reliable hydrometric gauges that provide annual maxima flood flow series. These are the Bellagill, Derrycahill, Rockwood and Willsbrook gauges, all of which are present on the mainline channel and all located upstream of Ballinasloe. Between the four gauges, they currently provide 270 station years of flood data, with individual records of typically 68 years at three gauges and 66years at one (Derrycahill 26005). Such records provide a reasonably long annual maxima flood flow sample for the consideration of single-site statistical analysis for flood flow estimation of extreme flood events. Combined, they also provide a local catchment-based geographical pooling group. The individual AM series for these gauges is presented in Figure 5-1 to Figure 5-4 and show reasonable consistency and correlation in respect to the flood patterns.

In particular, the more notable flood events captured at all four gauges are the 1954, 1968, 2009, 2015 and 2020 flood events and all four stations displaying similar distribution patterns.

At site, analysis involves fitting the statistical distributions presented in Table 5-1 to the individual AM series using the method of L-moments, which is the preferred method both by the UK FEH(1998) and the Irish FSU (2009).

The statistical fit of the different probability distributions are presented in Figure 5-5 to Figure 5-8 for the River Suck Gauges and demonstrate a considerable spread in distribution fit to the data. The computed return period flood quantiles QT are presented in Table 5-3 to Table 5-6, respectively.

The summary statistics in terms of L-moments are presented below in Table 5-2 for the four River Suck gauging sites along with the average Pooled L-moments.

Table 5-2 Computed L-moment statistics for the River Suck Gauges

Stn Ref	Gauge Name	River	years	QMED	L-CV	L-Skewness	L-Kurtosis
26007	Bellagill	Suck	68	93.6	0.135	0.201	0.236
26005	Derrycahill	Suck	66	89.1	0.111	0.171	0.259
26002	Rockwood	Suck	68	56.3	0.105	0.217	0.253
26006	Willsbrook	Suck	68	26.8	0.196	0.328	0.254
pooled			**270**		**0.137**	**0.229**	**0.251**

Note that QMED is the median of the available annual series of floods for the above gauges and has a return period of every 2years on average. The other statistical parameters coefficient of variation, skewness and kurtosis are also obtained from AM series.

As clear from Figure 5-5 to Figure 5-8, the different distribution types give varying fit to the AM data as presented in Gringorton plotting positions. The 3- parameter distributions with the shape factor (includes skewness) gives a better fit to the AM data, particularly with the almost outlier magnitude associated with the Nov 2009 flood event at three of the gauges 26007, 26005 and 25002. The 2-parameter distributions have a preset skewness (EV1 has L-skew of 0.1699 and the LO is zero) and, therefore less flexible to the site-specific data. The EV1 distribution, given the relatively low skewness of Irish flood data, is generally considered to be representative of Irish annual maxima flood data, but in this case, does not fit well the Suck gauges.

The problem with the three parameter distributions is that they suffer from much higher statistical (sample) error due to the additional parameter and, therefore, less robust and more biased to the sample statistics. The recommendation by the FSU is to use where feasible 2-parameter EV1 or LN2 for at-site gauged analysis and the 3-parameter GLO or GEV or LN3 at ungauged locations from a pooling group. This will depend on the data and the fit. The three-parameter distributions can depend on the shape parameter k (associated with skewness) value and can become upper-bounded and tend to a finite upper limit at increasing return period, which is not considered realistic for flood statistics. The GLO distribution becomes upper-bounded when the L-skewness falls below zero and the GEV suffers from this earlier when L-skewness falls below 0.1699.

The LP3 and the LN3 give relatively similar results as the GEV distribution for the Suck gauges with the GLO giving consistently higher quantile estimates than all of the distributions and generally fitting better the AM data for the four Suck gauge sites. The UK Flood Estimation Handbook favours the GLO distribution over the GEV and other distributions as it suffers less from being upper-bounded and is likely to error on overprediction.

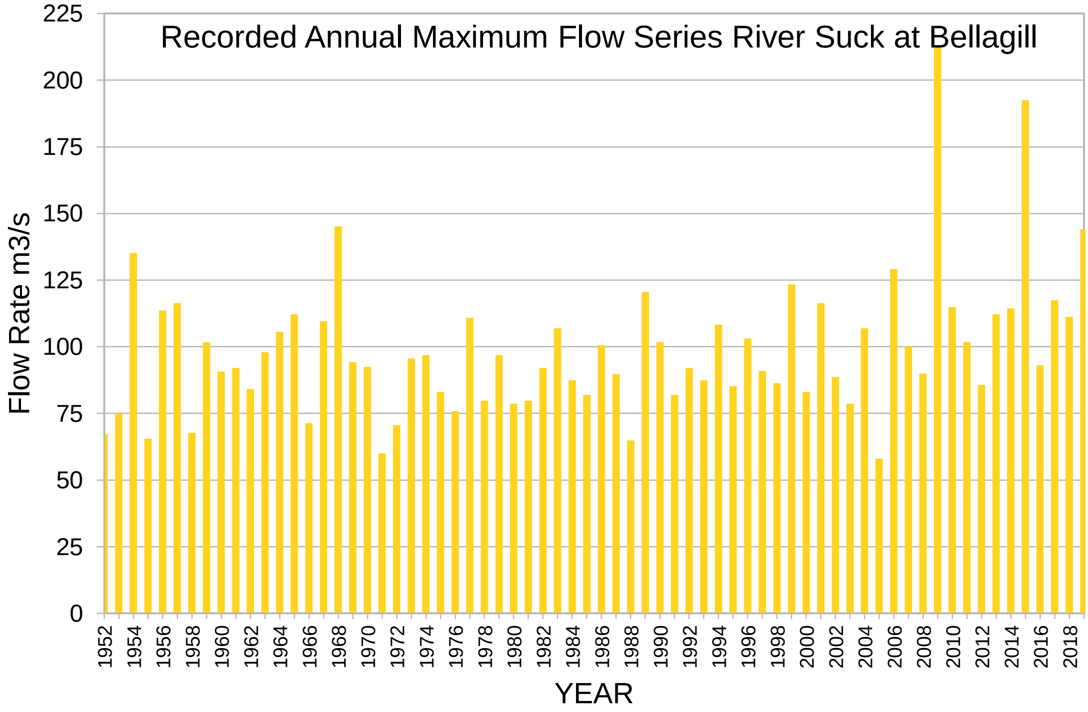

Figure 5-1 Annual Maximum Flood flow Series for River Suck at Bellagill (26007) gauge

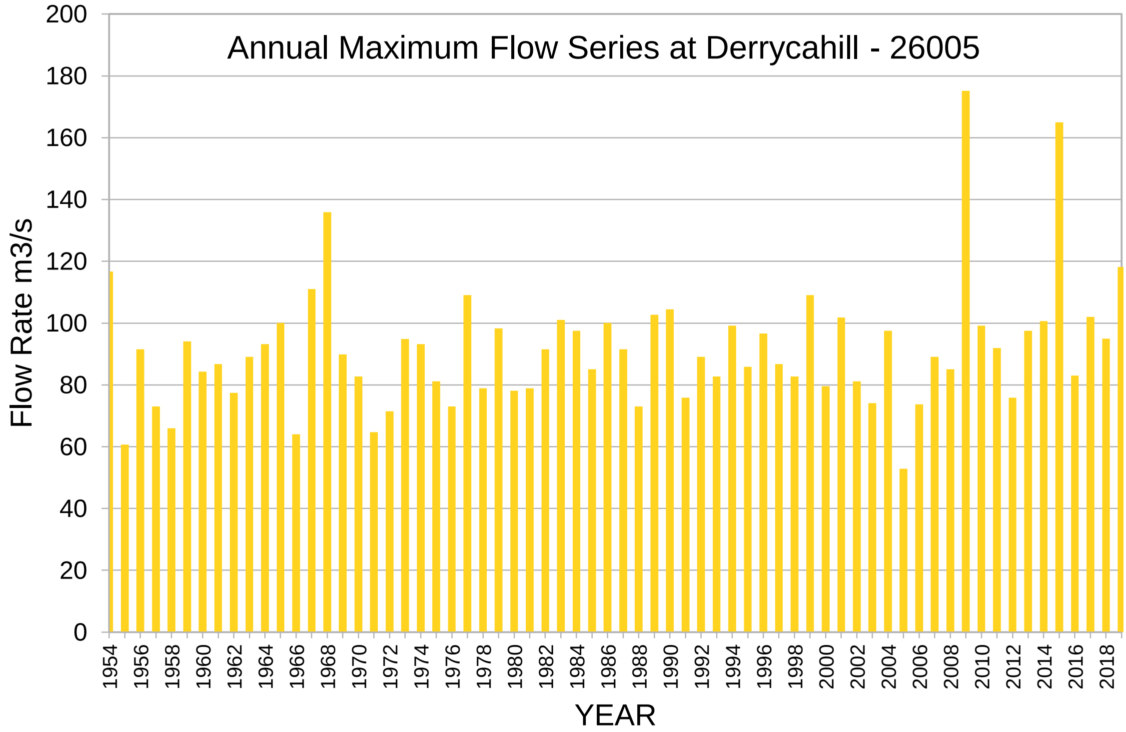

Figure 5-2 Annual Maximum Flood flow Series for River Suck at Derrycahill (26005) gauge

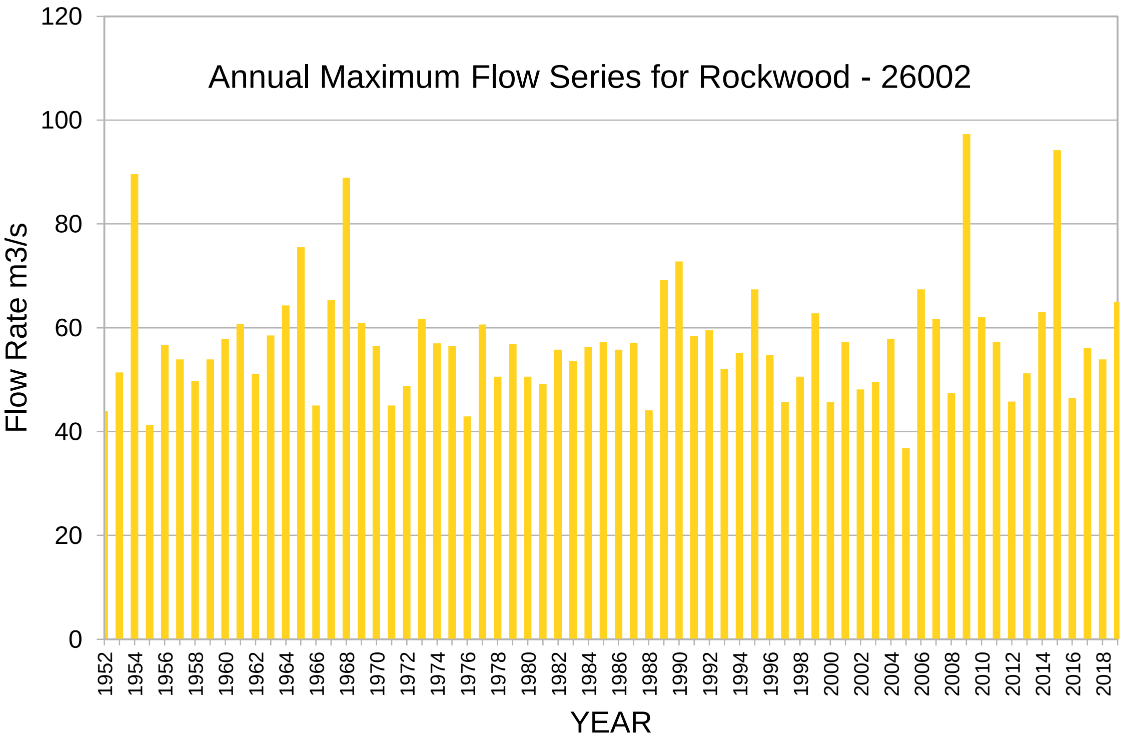

Figure 5-3 Annual Maximum Flood flow Series for River Suck at Rockwood (26002) gauge

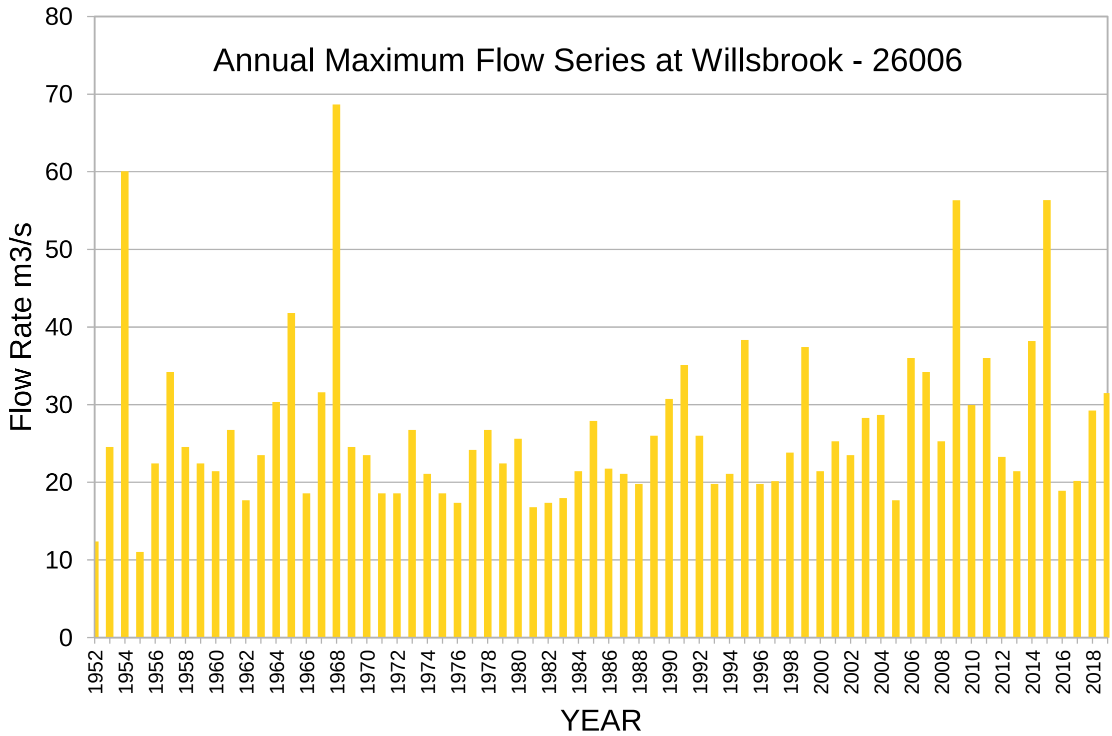

Figure 5-4 Annual Maximum Flood flow Series for River Suck at Willsbrook (26006) gauge

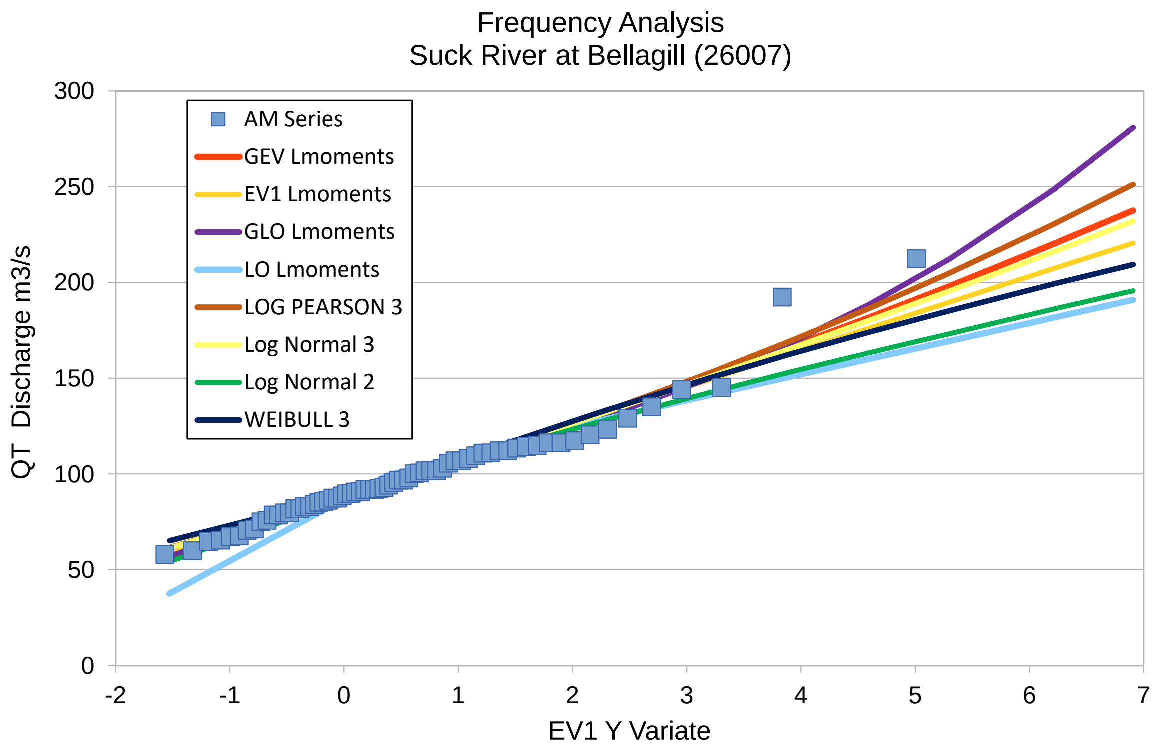

Figure 5-5 Statistical fit of selected probability distributions to the AM Flood data at Bellagill

Table 5-3 Computed Return Period Flood Flow Quantiles QT for the River Suck at Bellagill (26007) using different probability distributions

Return Period T	EV1	GEV	GLO	LO	LP3	LN3	LN2	Weibull
2	94.8	94.1	94.5	98.8	93.6	94.1	95.9	93.9
5	116.6	115.9	114.4	117.3	116.0	116.2	117.3	117.5
10	131.0	130.9	128.9	128.1	131.7	131.2	130.3	132.5
25	149.2	145.9	149.9	141.2	152.7	150.6	145.7	150.2
50	162.7	166.1	168.0	150.7	169.3	165.3	156.6	162.5
100	176.2	181.8	188.6	160.1	186.5	180.2	167.1	174.1
200	189.5	198.0	212.1	169.4	204.7	195.3	177.4	185.2
500	207.2	220.1	248.5	181.6	230.4	215.9	190.7	199.2
1000	220.5	237.6	280.8	190.9	251.2	232.0	200.5	209.3

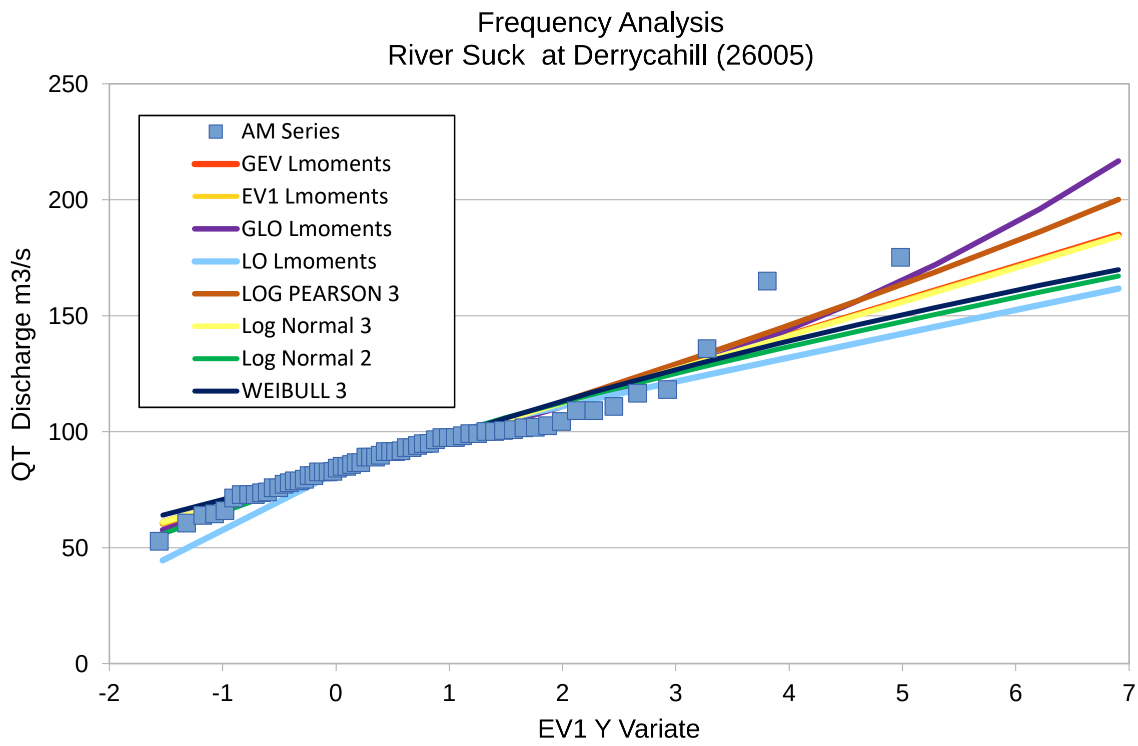

Figure 5-6 **Statistical fit of selected probability distributions to the AM Flood data at Derrycahill**

Table 5-4 **Computed Return Period Flood Flow Quantiles QT for the River Suck at Derrycahill (26005) using different probability distributions**

Return Period T	EV1	GEV	GLO	LO	LP3	LN3	LN2	Weibull
2	88.3	87.9	88.6	91.4	87.7	88.3	89.5	88.2
5	104.9	104.3	103.7	105.5	105.1	105.1	106.1	105.9
10	116.0	115.2	114.4	113.8	117.0	116.0	116.0	116.8
25	129.9	128.8	129.5	123.8	132.4	129.8	127.5	129.4
50	140.2	139.0	142.2	131.0	144.3	139.9	135.5	138.0
100	150.5	149.0	156.3	138.2	156.4	150.1	143.2	146.0
200	160.7	159.1	172.1	145.3	168.9	160.2	150.6	153.6
500	174.2	172.3	196.0	154.7	186.3	173.8	160.1	163.1
1000	184.4	182.3	216.7	161.7	200.1	184.2	167.2	169.9

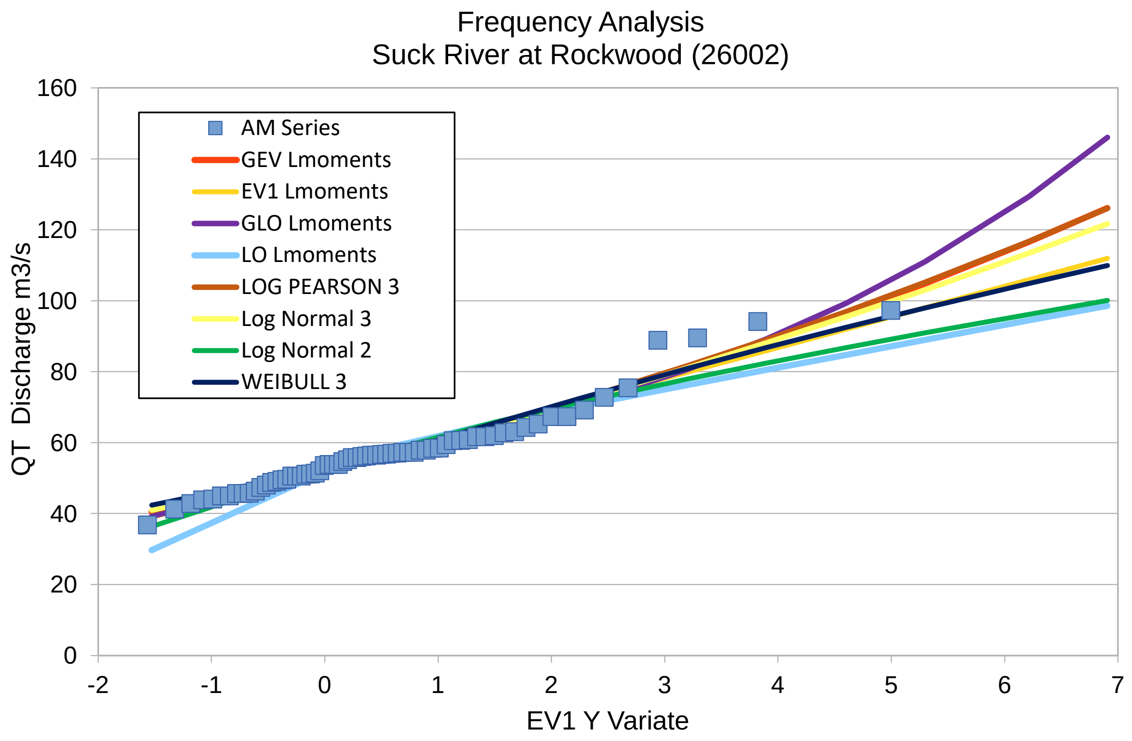

Figure 5-7 Statistical fit of selected probability distributions to the AM Flood data at Rockwood

Table 5-5 Computed Return Period Flood Flow Quantiles QT for the River Suck at Rockwood (26002) using different probability distributions

Return Period T	EV1	GEV	GLO	LO	LP3	LN3	LN2	Weibull
2	55.5	55.0	55.2	57.3	54.9	55.0	56.3	56.4
5	65.3	64.8	64.2	65.6	65.1	65.0	65.8	67.4
10	71.8	71.7	70.8	70.5	72.2	71.9	71.5	74.5
25	80.0	81.0	80.6	76.4	81.6	81.0	78.0	83.0
50	86.1	88.4	89.1	80.6	88.9	88.0	82.5	89.0
100	92.1	96.0	98.9	84.9	96.6	95.1	86.8	94.7
200	98.1	104.1	110.3	89.0	104.6	102.5	91.0	100.2
500	106.1	115.3	128.1	94.6	115.8	112.5	96.2	107.1
1000	112.1	124.3	144.1	98.7	124.9	120.5	100.1	112.1

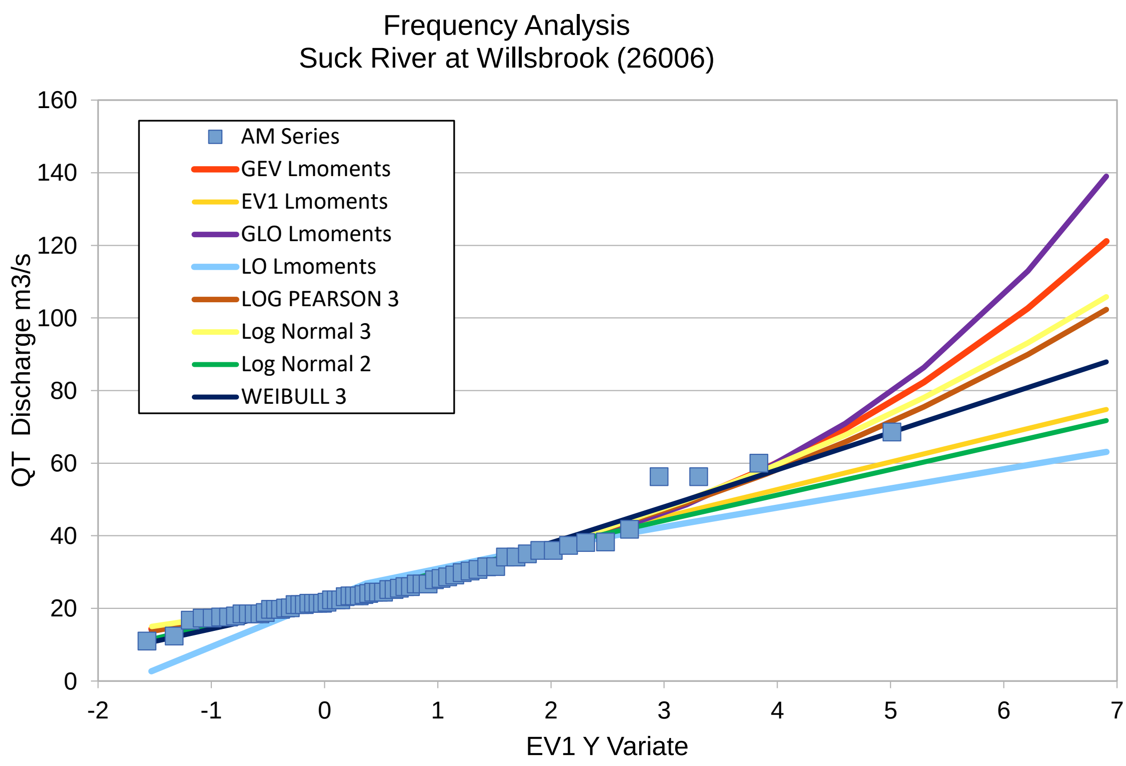

Figure 5-8 **Statistical fit of selected probability distributions to the AM Flood data at Willsbrook.**

Table 5-6 **Computed Return Period Flood Flow Quantiles QT for the River Suck at Willsbrook (26006) using different probability distributions**

Return Period T	EV1	GEV	GLO	LO	LP3	LN3	LN2	Weibull
2	25.2	24.0	24.1	26.8	24.3	23.9	25.2	24.0
5	33.8	32.2	31.8	34.1	32.9	32.6	33.5	33.8
10	39.5	38.9	38.2	38.4	39.6	39.6	38.9	41.1
25	46.7	49.3	48.6	43.5	49.1	49.8	45.6	50.7
50	52.0	58.6	58.5	47.3	57.0	58.4	50.5	58.0
100	57.3	69.5	70.9	50.9	65.8	67.8	55.4	65.2
200	62.6	82.3	86.4	54.6	75.5	78.1	60.3	72.5
500	69.5	102.6	112.9	59.4	89.9	93.2	66.8	82.0
1000	74.8	121.1	139.0	63.1	102.3	105.8	71.7	89.2

The AMAX series at all of the four Suck Sites do not give a consistent shape for a good fit by any of the above statistical distribution with the larger flood events that include the 2009 and 2015 events significantly pulling up the AMAX series when plotted logistically using Gringorten plotting positions. Such characteristics present as a step/discontinuity in the distribution. This characteristic is also mirrored at other gauges on the River Shannon system, at Athlone, Banagher, Boyle Abbey and Jamestown associated with the 2009 and 2015 flood magnitudes. As a consequence the above eight distributions fitted to data are not well represented by the data.

The GLO distribution with its upward curving nature best represents this upward departure over the other distributions fitted. For long AMAX series such as the River Suck at its four gauges (68year AMAXs at each station) the flood magnitudes of 2009 and 2015 due to their significantly higher flow magnitudes over remaining AMAX values appear as outliers and not typical of the general trend. However, evidence from AM series at other gauging stations on the Shannon and other rivers present similar patterns suggesting that these events cannot be dismisses as outliers and should be included for and thus the justification for the selection of the GLO distribution fit. Of greater concern is that the flood events on the suck no longer satisfy the assumption of being from a single statistical distribution possibly attributed to climate change and increased winter rainfall.

Of the eight distributions fitted to the AMAX series three distributions are selected for further analysis, namely GLO, GEV and EV1 as they best represent the bulk of the distributions fitted with the EV1 representing the 2-parameter statistical distribution and GEV the 3-parameter distribution and the GLO being the recommended distribution. Both the EV1 and the GEV are generally the distributions of choice for fitting to Irish flood series with EV1 the best fit distribution to Irish catchments followed by GEV. GLO is the preferred distribution for British catchments and used for this study to allow for the observed lifting of the Growth curve by the recent extreme 2009 and 2015 flood events on the Suck and Shannon Catchments.

5.3.2 Statistical Standard Error Analysis

The statistical standard error for the EV1, GEV and GLO distributions was investigated by performing Monte-Carlo simulation for return periods of 2, 5, 10, 25, 50, 100, 200, 500 and 1000. This was carried out by generating 1000 random synthetic AM series of a sample size equivalent to the gauged AM sample size from a parent distribution defined by the measured L-moments for Bellagill, Derrycahill, Rockwood and Willsbrook. The percentage standard errors for QMED, Q100 and Q1000 were found to be 2.3 to 4.3%, 5.4 to 7.9% and 6.5 to 8.4%, respectively for the EV1 distribution, 2.5 to 4.4%, 9.3 to 20.7% and 24.3 to 46.2% respectively for the GEV distribution and 2.3 to 4.2%, 11.6 to 23.7% and 24.7 to 56.8% respectively for the GLO distribution, refer to Table 5-7 to Table 5-9 and Figure 5-9 to Figure 5-20.

As expected, the EV1, which is a 2-parameter distribution, has the lowest associated standard error. The computed standard errors associated with the GEV and GLO are significantly higher due to its third parameter (skewness), with the GLO slightly higher than the GEV. The standard error is a sampling error based on sample size and sampled statistics moments (i.e. coefficient of variation and skewness) and does not include model error, measurement error and assumptions in respect to homogeneity and stationarity.

The EV1 has a low statistical error but represents the poorest fit to the gauged data, whereas the GLO appears to have the best fit to the data but the highest statistical error, refer to Figure 5-9 to Figure 5-20.

The difficulty with only accounting for statistical error is that it is not a measure of the suitability of the chosen distribution.

Theoretical expressions for L-moment based estimates of Q_T for EV1 and GEV distributions have been given in a journal paper by Lu and Stedinger (1992). For Samples drawn from the EV1 distribution, the following expression applies:

$$SE\left[\widehat{Q_T}\right] = \frac{\propto}{\sqrt{N}}\sqrt{1.1128 + 0.4574y_T + 0.8046{y_T}^2} \qquad (7)$$

Where $\widehat{Q_T}$ is the estimate for the T-year flow event, $\propto$ is the EV1 scale factor and y_T is the EV1 reduced variate and N is the number of observations (i.e. number of AM years in the series). This equation, when applied to the four Suck stations, give similar results to the Monte-Carlo Simulation (c. difference in SE of < 5%).

For sample drawn from the GEV distribution, the following expression applies:

$$SE\left[\widehat{Q_T}\right] = \frac{\propto}{\sqrt{N}}\left[e^{\left\{a_0+a_1e^{-k}+a_2e^{k^2}+a_3e^{k^3}\right\}}\right]^{0.5} \qquad (8)$$

Where a_0, a_1, a_2, a_3 are coefficients that are a function of the return period with the values available in Lu and Stedinger (1992). This equation when applied to the four Suck stations give similar results to the Monte- Carlo Simulation (c. difference in SE of up to 7.5%). The Monte-Carlo simulation is considered to be more accurate than this regression equation.

There is currently no standard error expression derived for samples drawn from the GLO distribution. A comparison between GLO and GEV Monte-Carlo simulations show that for the Suck gauges the GLO distribution has standard errors of c. 6%, 19% and 30% higher than the GEV for 10, 100 and 1000years. The FSU had recommended that the GEV sample error from Lu and Stedinger (1992) be used as representative of error associated with GLO distribution which is not the case based on the above results.

Table 5-7 Computed Percentage Statistical Standard Error of the EV1 Distribution fitted to the River Suck Gauges based on the L-moments presented in Table 5-2

Gauge reference	Return Period								
	2	**5**	**10**	**25**	**50**	**100**	**200**	**500**	**1000**
26007	2.96	3.87	4.52	5.24	5.68	6.07	6.41	6.80	7.05
26005	2.40	3.28	3.90	4.61	5.05	5.44	5.79	6.19	6.46
26002	2.28	3.19	3.83	4.55	5.01	5.41	5.77	6.19	6.46
26006	4.39	5.25	5.91	6.60	7.01	7.36	7.65	7.99	8.19

Table 5-8 Computed Percentage Statistical Standard Error of the GEV Distribution fitted to the River Suck Gauges based on the L-moments presented in Table 5-2

Gauge reference	Return Period								
	2	5	10	25	50	100	200	500	1000
26007	3.21	3.87	4.79	6.87	9.01	11.64	14.68	19.39	23.38
26005	2.63	3.20	3.89	5.49	7.15	9.14	11.44	14.91	17.85
26002	2.45	3.21	4.17	6.30	8.52	11.29	14.58	19.82	24.44
26006	4.35	5.83	7.80	12.13	16.68	22.39	29.45	41.13	52.24

Table 5-9 Computed Percentage Statistical Standard Error of the GLO Distribution fitted to the River Suck Gauges based on the L-moments presented in Table 5-2

Gauge reference	Return Period								
	2	5	10	25	50	100	200	500	1000
26007	3.01	3.75	5.13	8.01	10.91	14.48	18.83	25.74	32.03
26005	2.44	3.11	4.21	6.49	8.82	11.65	15.03	20.45	25.32
26002	2.29	3.04	4.31	7.00	9.79	13.33	17.69	24.90	31.65
26006	4.33	5.75	8.23	13.48	18.93	25.88	34.59	49.89	65.30

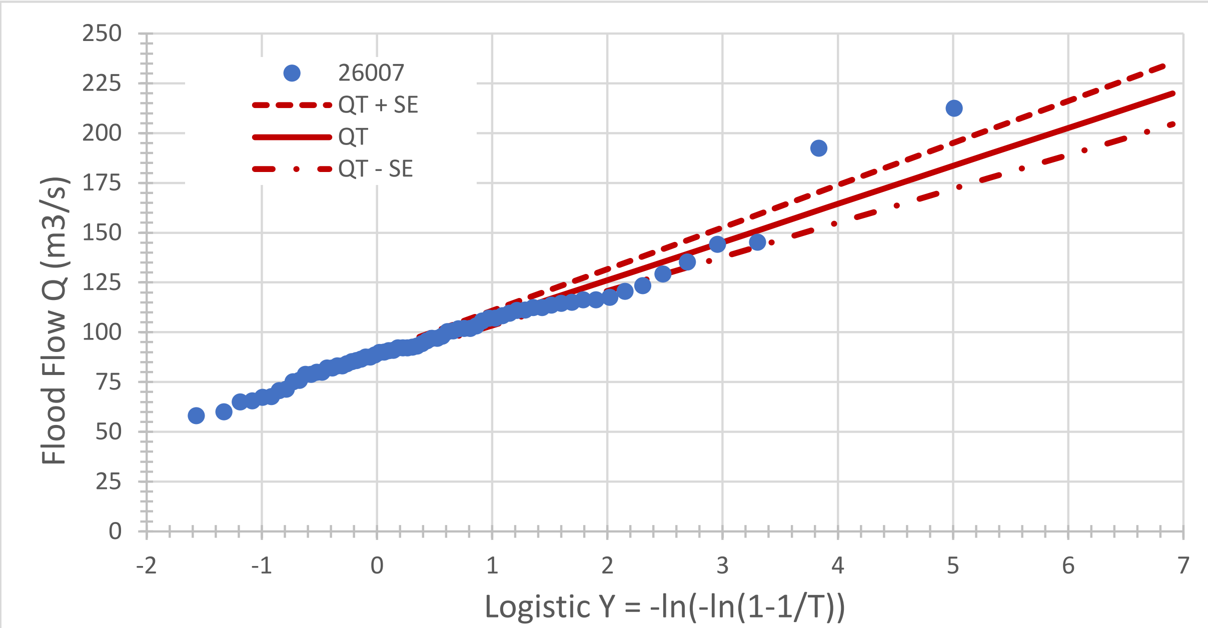

Figure 5-9 EV1 Fit with 67% confidence intervals - gauge 26007

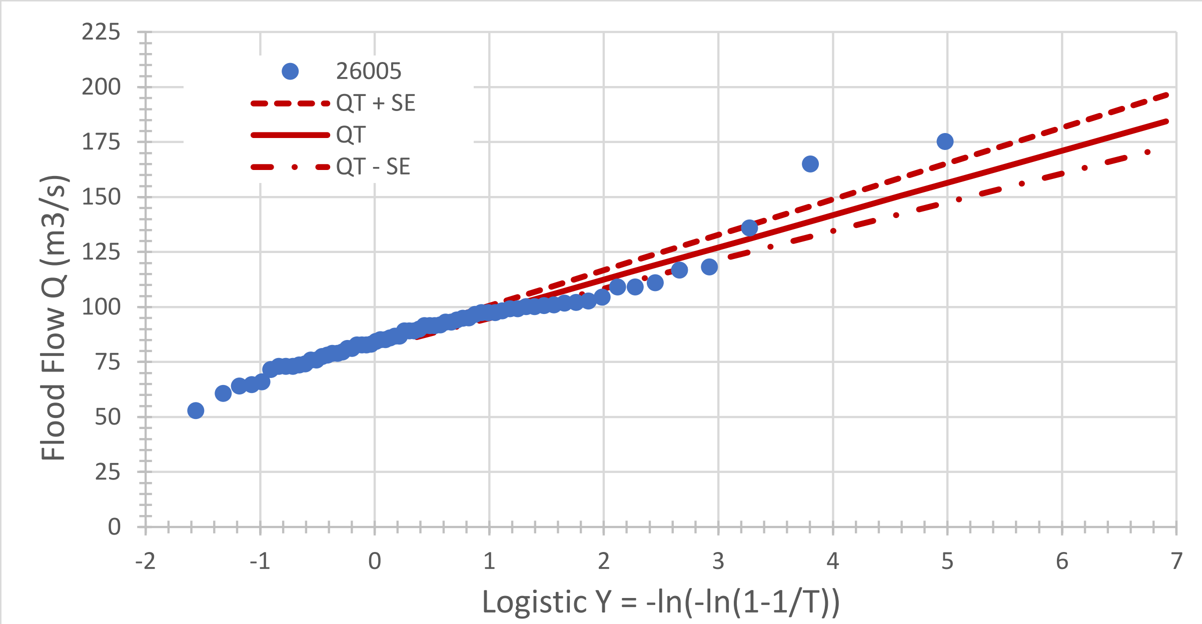

Figure 5-10 EV1 Fit with 67% confidence intervals - gauge 26005

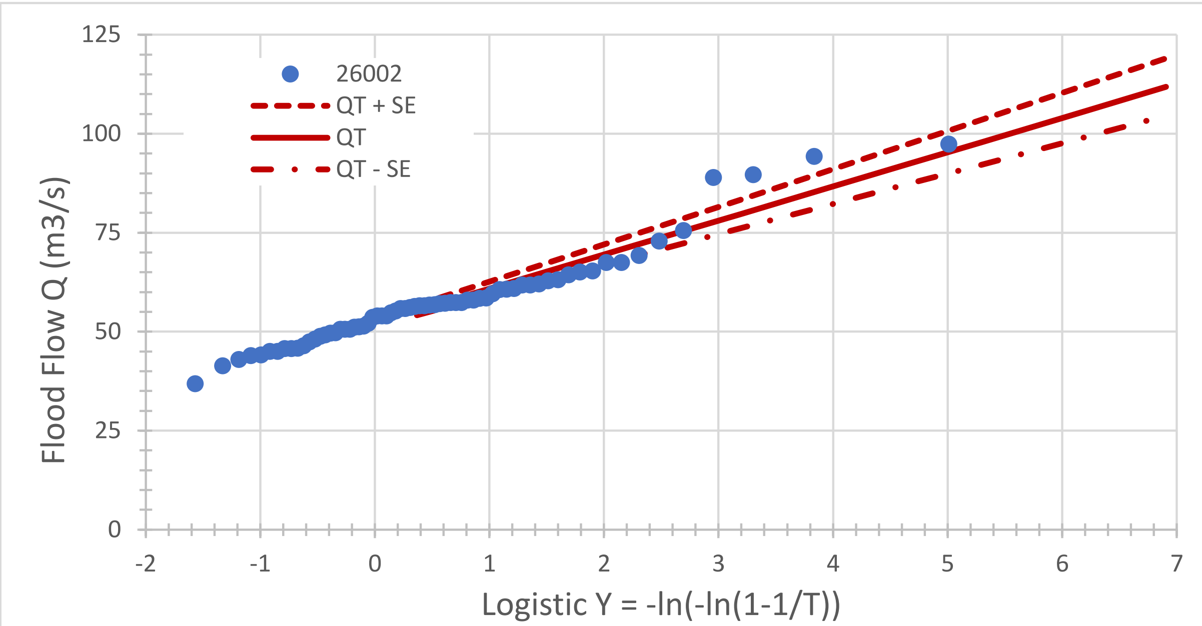

Figure 5-11 EV1 Fit with 67% confidence intervals - gauge 26002

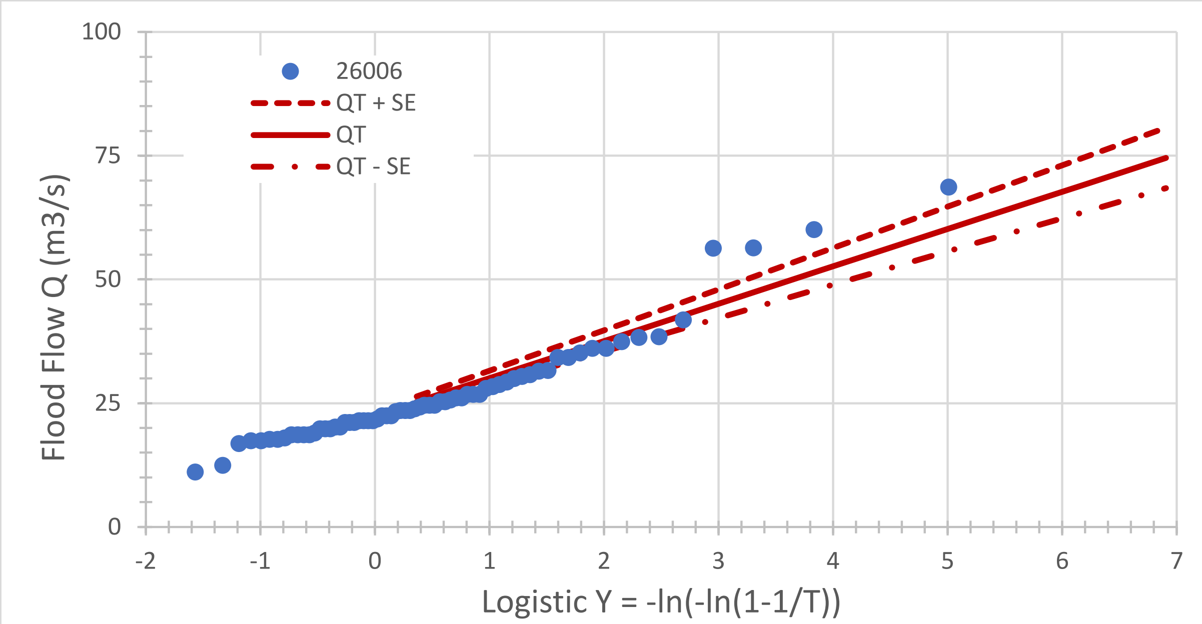

Figure 5-12 EV1 Fit with 67% confidence intervals - gauge 26006

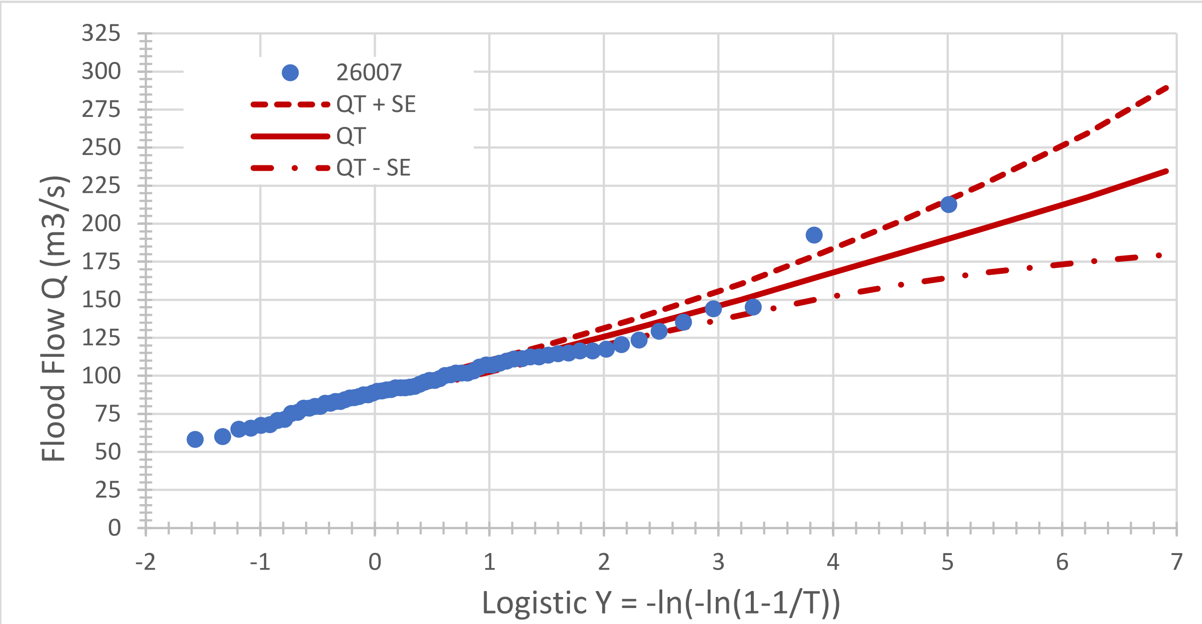

Figure 5-13 GEV Fit with 67% confidence intervals - gauge 26007

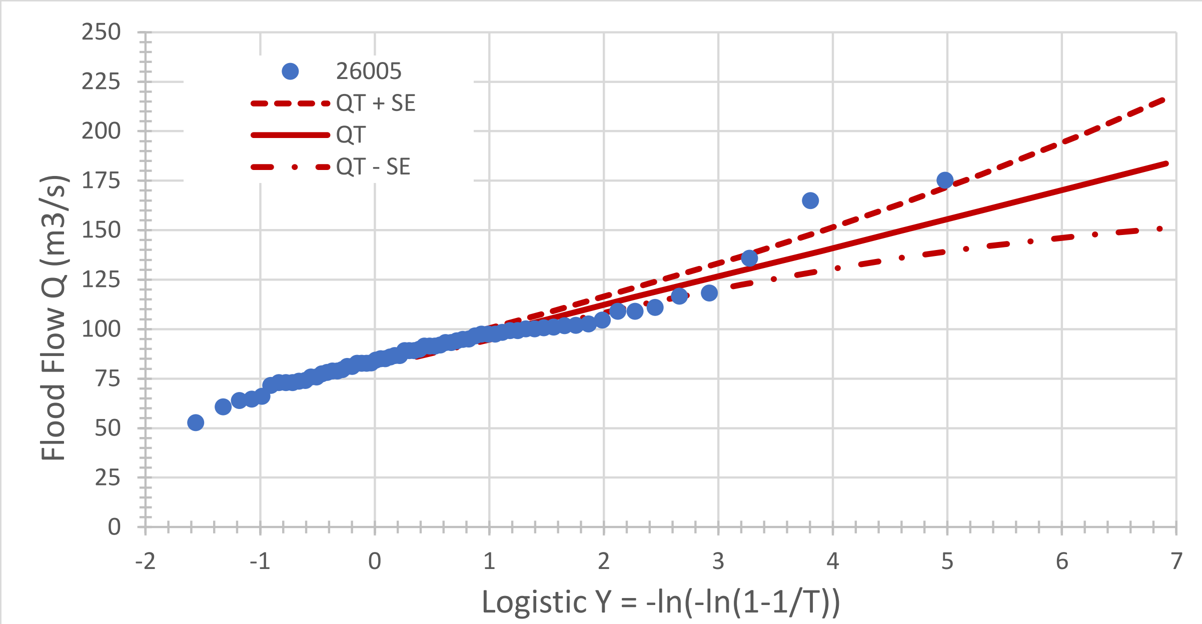

Figure 5-14 GEV Fit with 67% confidence intervals - gauge 26005

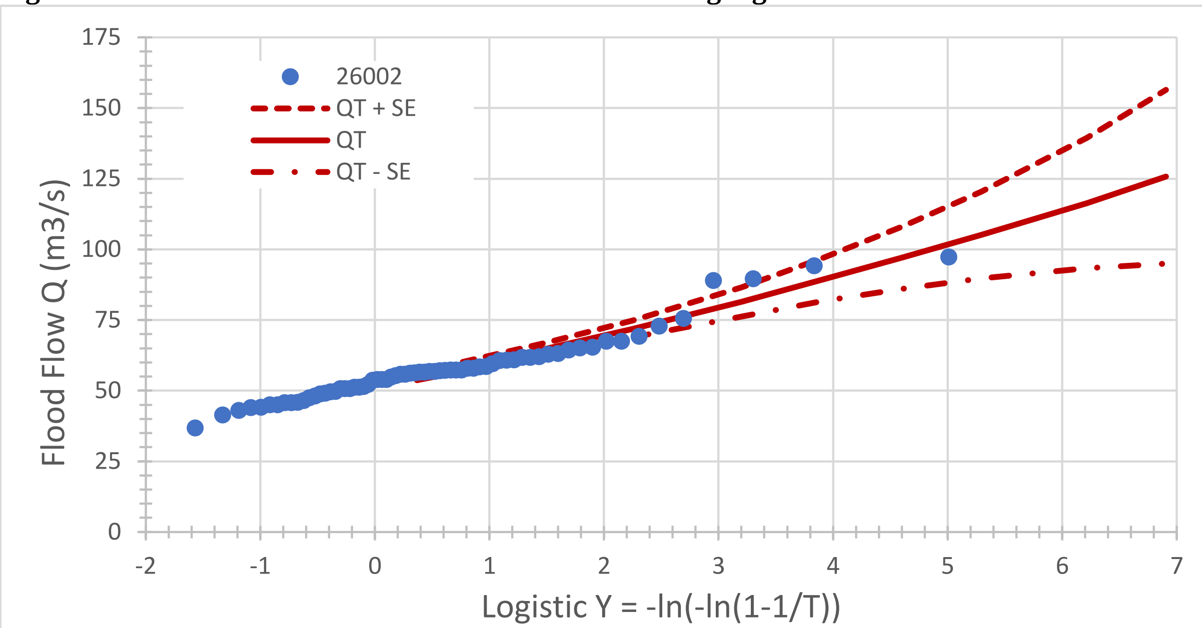

Figure 5-15 GEV Fit with 67% confidence intervals - gauge 26002

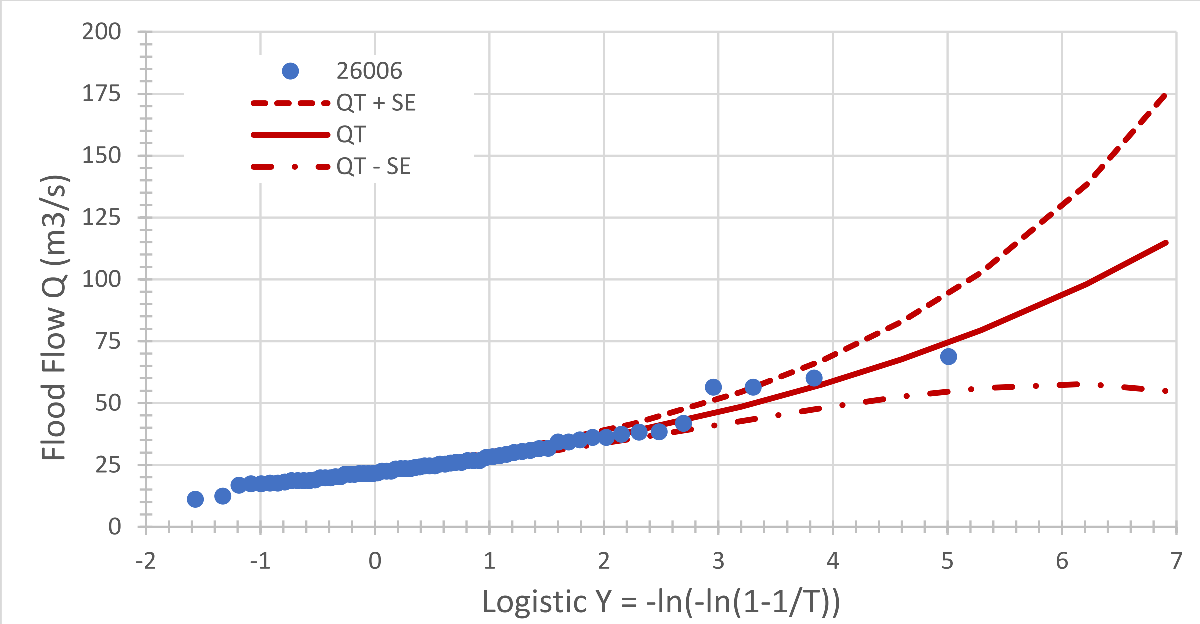

Figure 5-16 GEV Fit with 67% confidence intervals - gauge 26006

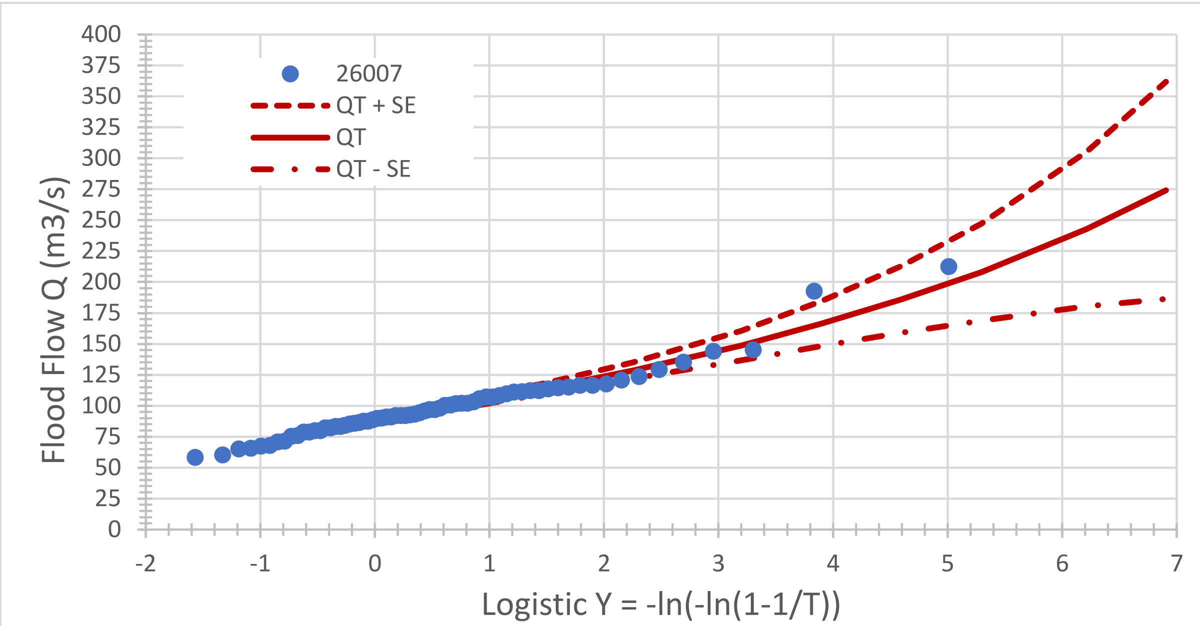

Figure 5-17 GLO Fit with 67% confidence intervals - gauge 26007

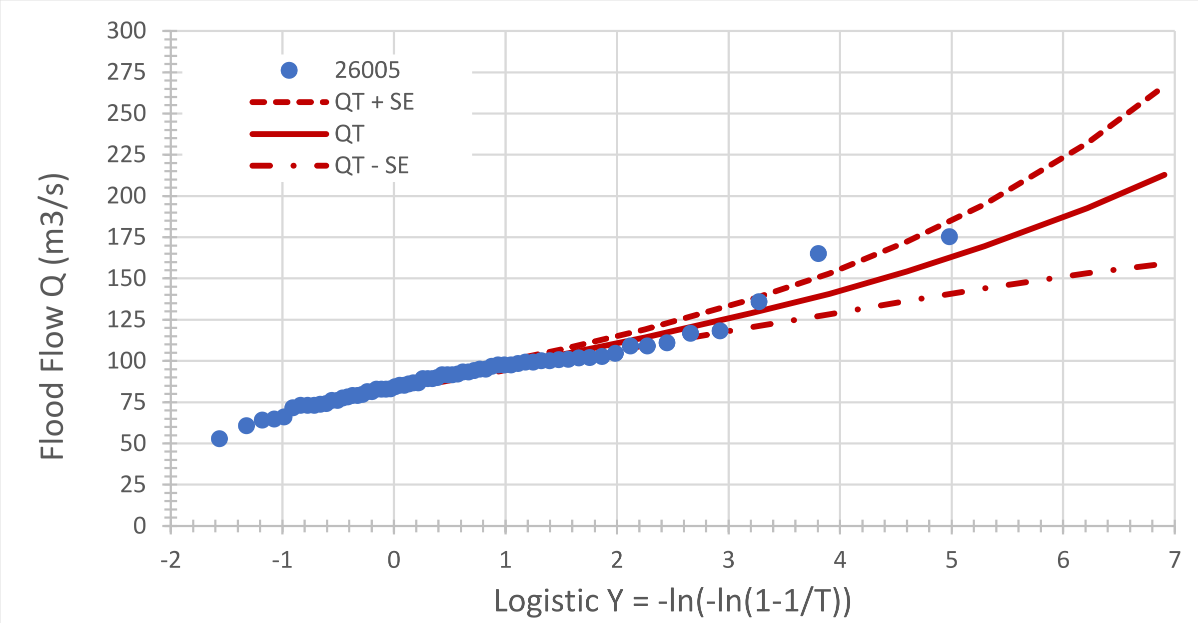

Figure 5-18 GLO Fit with 67% confidence intervals - gauge 26005

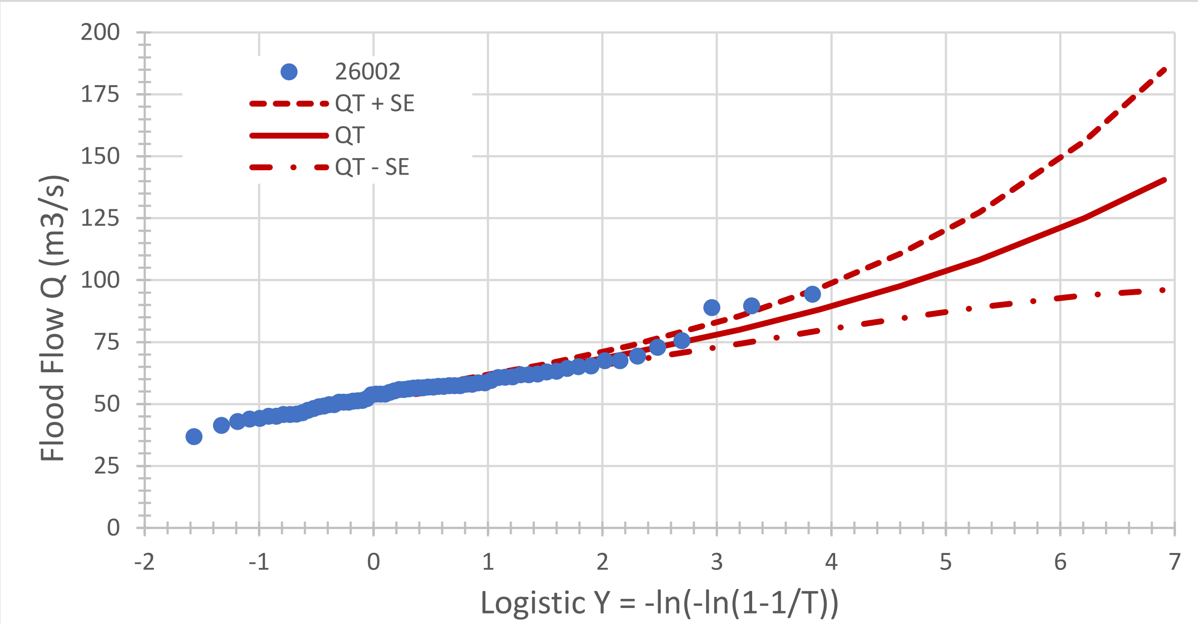

Figure 5-19 GLO Fit with 67% confidence intervals - gauge 26002

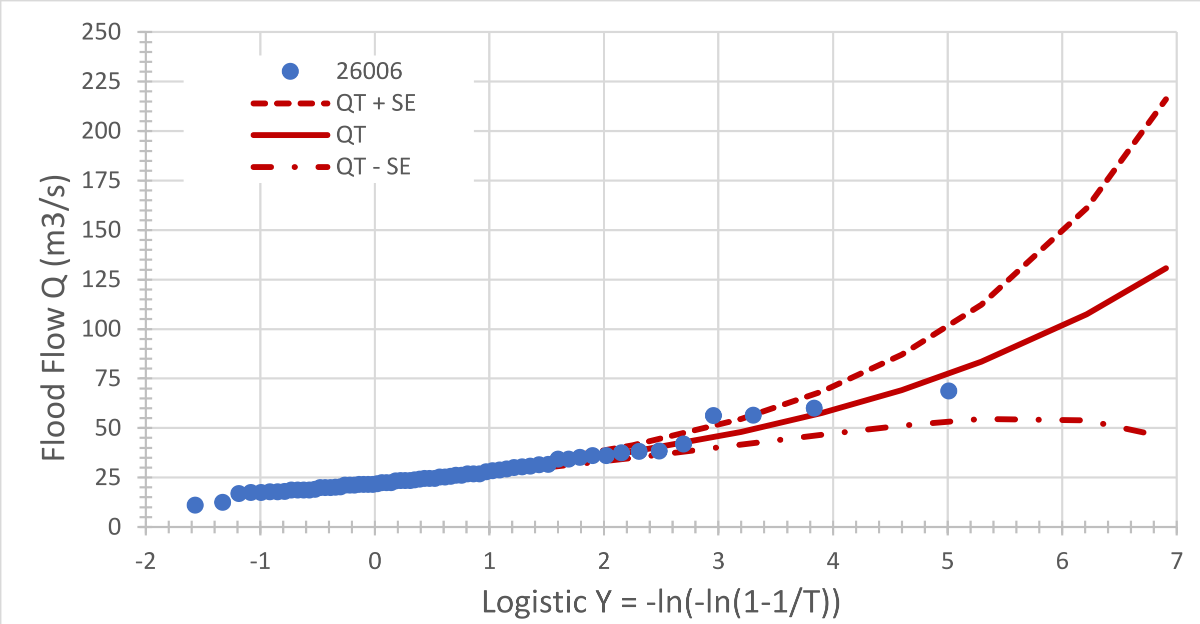

Figure 5-20 GLO Fit with 67% confidence intervals - gauge 26006

5.4 Flood Growth Curve from Pooled Analysis

5.4.1 Introduction

The flood growth curve from pooled analysis uses the concept of a region-of-influence approach involving the creation of a collection of hydrologically similar catchments. To avoid over reliance on a single gauge site and its associated high statistical error, it is recommended in the FSU and the FEH to select a pooling group of hydrologically similar gauges. The assumption that is inherent in the pooling group is that they represent a homogenous group whose growth factor X_T originates from a single-parent population. This involves standardization by dividing the AM series of quantiles for each selected gauge by its respective QMED value. The assumption is that the standardized series for the pooling group have been derived from the same population having the same L-cv and L-skewness values.

In theory, the standard error of the X_T estimate should be reduced by the order of $\sqrt{m}$, where m is the number of homogenous gauges in the pooling group. In reality, however, the selected group is often not very homogenous and therefore, the real statistical error is likely not to achieve anywhere close to the above reduction. It can, in many cases be potentially less reliable with an averaging effect occurring in respect to its L-cv and L-skewness due to the inclusion of unsuitable sites, that might even have reasonably similar PCDs to the subject site but their AM series do not reflect this, possibly due to measurement error or regional/location differences. Consideration of the spread of L-cv and L-skewness within the pooling group is important before recommending the use of a pooling growth curve or the final selection of candidate sites.

5.4.2 Pooled Growth Curves

Two pooling groups for the River Suck to Bellagill were considered namely a local pooling group of the 4 River Suck gauges (26007, 26005, 26006 and 26002), providing 270station years and a pooling group based on the FSU PCDs Euclidean distance method providing a selection of eight stations and combined 476 station years).

The local pooling group of River Suck gauges provides a pooled L-cv and L-skew of 0.137 and 0.229, respectively. Figure 5-21 to Figure 5-23 present the individual and pooled Growth Curve for EV1, GEV and GLO distributions. Table 5-10 presents the computed return period growth factors for the three distributions based on the average growth curve of the four River Suck gauges.

Table 5-10 Pooled Growth Factors X_T based on the four River Suck Gauges

Return Period T years	X_T EV1	X_T GEV	X_T GLO
5	1.23	1.23	1.22
10	1.39	1.41	1.38
25	1.58	1.64	1.63
50	1.73	1.86	1.86
100	1.87	2.08	2.12
200	2.02	2.33	2.44
500	2.21	2.69	2.96
1000	2.35	3.00	3.45

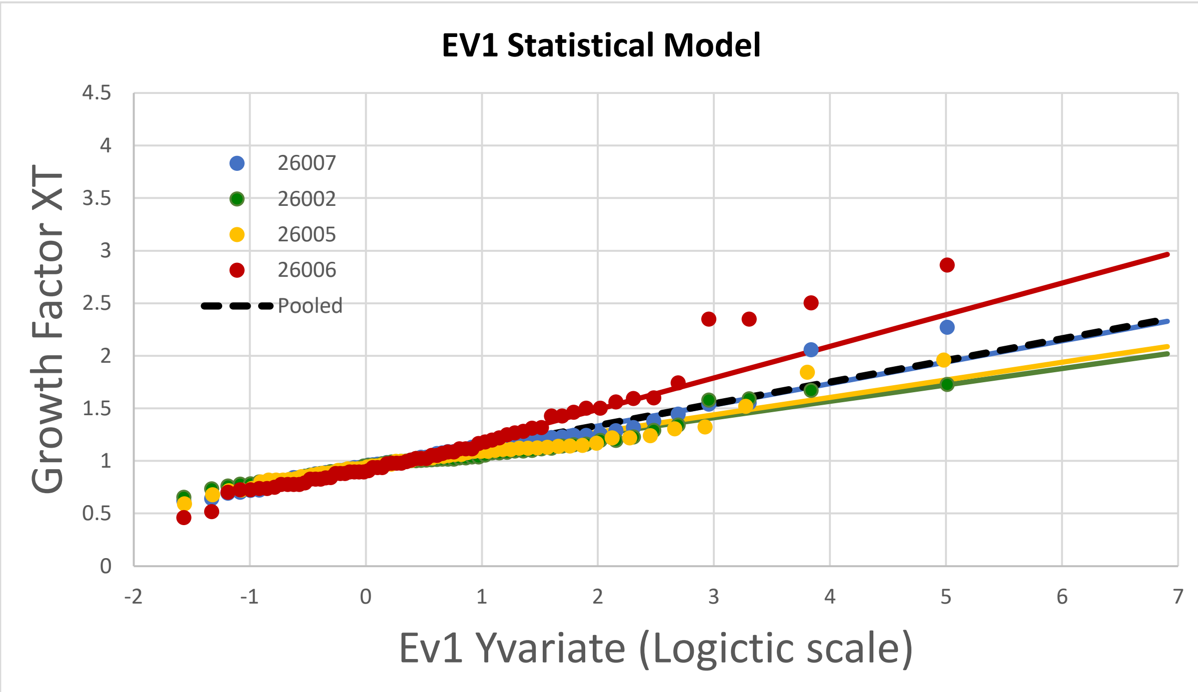

Figure 5-21 Flood Growth Curves based on EV1 distribution of pooled River Suck Gauges

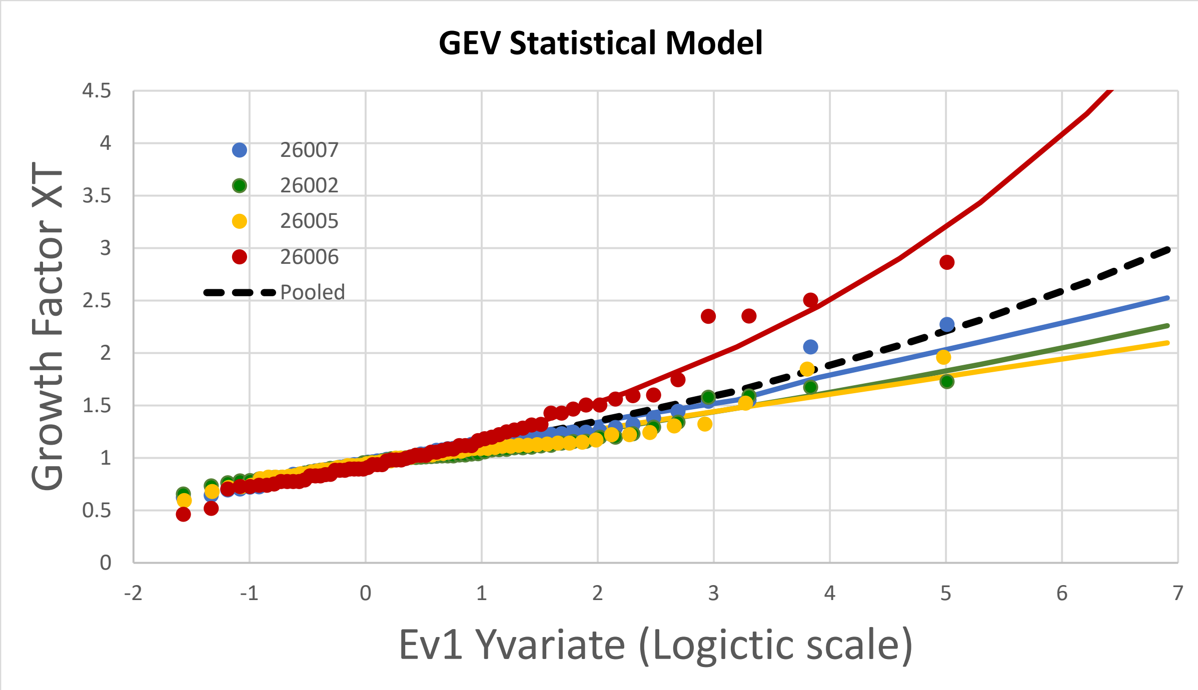

Figure 5-22 Flood Growth Curves based on GEV distribution of pooled River Suck Gauges

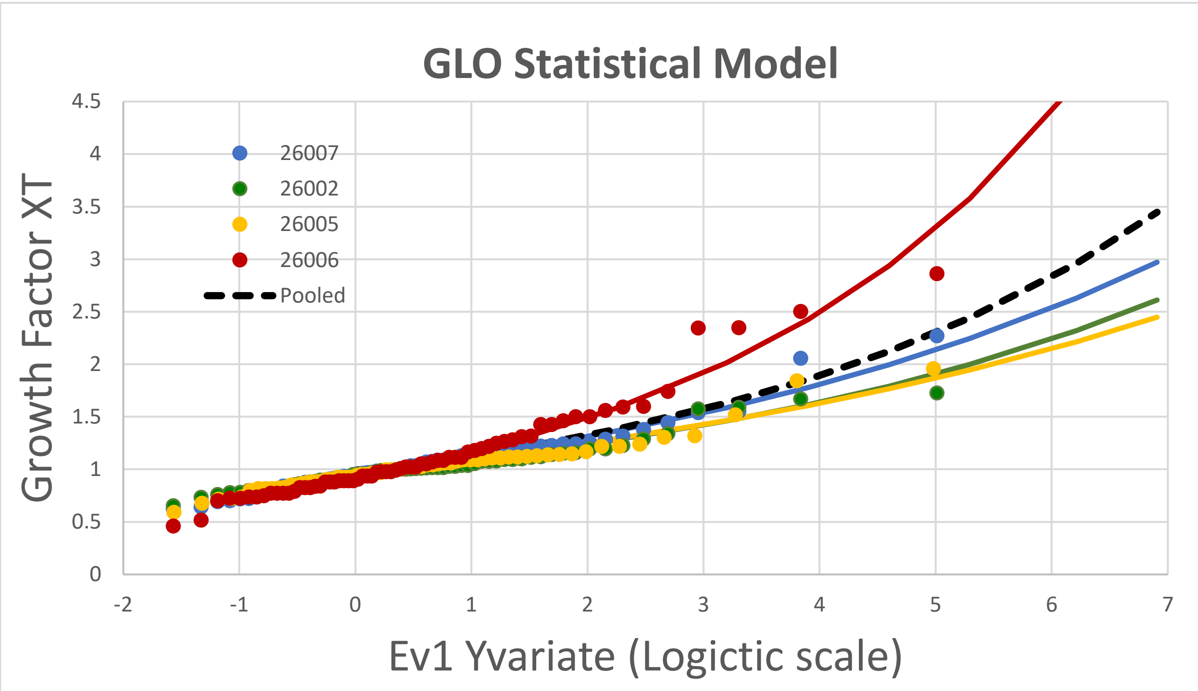

Figure 5-23 Flood Growth Curves based on GLO distribution of pooled River Suck Gauges

The FSU pooling group method resulted in the following gauged stations being selected based on hydrological similarity, refer to Table 5-11 below. The Euclidean distance measure d_{ij} (equation 9 below) from the FSU is used to select the pooling group gauges.

$$d_{ij} = \sqrt{\left(\frac{ln(AREA_i)-ln(AREA_j)}{\sigma_{lnAREA}}\right)^2 + \left(\frac{ln(SAAR_i)-ln(SAAR_j)}{\sigma_{lnSAAR}}\right)^2 + \left(\frac{ln(BFIsoil_i)-ln(BFIsoil_j)}{\sigma_{lnBFIsoil}}\right)^2} \qquad (9)$$

Where the standard deviations of the complete FSU gauged set is σ_{lnAREA}=1.265, σ_{lnSAAR}=0.173 and $\sigma_{lnBFIsoil}$= 0.219.

Within the pooling group identified by the Euclidean distance selection, three stations were identified, namely 15012, 30012 and 07010, whose AM series are very short for statistical analysis and whose AM series are no longer available (no longer considered reliable post FSU) are dropped from the final pooling group selection. The available stations are presented in Table 5-11 below, and the hydrological similarity value to Bellagill and Ballinasloe are presented in Table 5-12.

This initial group of 9 stations was reduced to 8 stations after rejecting the River Suir at Cahir Park, based on skewness which would present an unrealistic limit to the upper bound to the respective growth curve having negative L-skewness. The remaining eight stations provide 476 station years and give an average L-cv of 0.1349 and L-skewness of 0.201. Refer to **Table 5-13**.

Table 5-11 FSU Physical Catchment Descriptors of pooling group

Station	Location	AREA (km^2)	SAAR (mm)	BFIsoil (index)	FARL (index)	DRAIND (km/km2)	S1085 (m/km)	MSL (km)	ARTDRAIN2 (Prop)	URBEXT (Prop)
26007	BELLAGILL	1207.2	1046	0.653	0.983	0.753	0.413	107.355	0.000	0.002
16008	NEW BRIDGE	1090.3	1030	0.635	0.999	0.986	0.921	68.615	0.000	0.007
16009	CAHER PARK	1582.7	1079	0.631	0.998	1.002	1.005	85.436	0.000	0.008
36010	BUTLERS BR.	771.7	968	0.632	0.861	1.005	1.581	64.306	0.000	0.005
26002	ROOKWOOD	641.5	1067	0.605	0.979	0.799	0.559	72.332	0.000	0.003
30004	CORROFIN	699.3	1104	0.606	0.992	0.796	0.868	65.660	0.702	0.007
16011	CLONMEL	2143.7	1125	0.670	0.998	1.045	0.953	116.477	0.000	0.007
15002	JOHNS BRIDGE	1644.1	945	0.625	0.998	0.913	0.779	88.542	0.003	0.010
26005	DERRYCAHILL	1085.4	1054	0.560	0.981	0.756	0.461	96.713	0.000	0.002

Table 5-12 FSU River Suck pooling group to Ballinasloe

Rank	Station	Name	River	AREA	SAAR	BFISoil	Hydrological Similarity	
							Bellagill	Ballinasloe
1	26007	Bellagill	Suck	1207.2	1046	0.653	0.000	0.438
2	16008	Newbridge	Suir	1090.3	1030	0.635	0.175	0.373
3	16009	Cahir	Suir	1582.7	1079	0.631	0.320	0.321
4	36010	Butler's Bridge	Annalee	771.7	968	0.632	0.590	0.721
5	26002	Rockwood	Suck	641.5	1067	0.605	0.618	0.645
6	30004	Corofin	Clare	699.3	1104	0.606	0.632	0.644
7	16011	Clonmel	Suir	2143.7	1125	0.670	0.630	0.746
8	15002	St. John's	Nore	1644.1	945	0.625	0.666	0.646
9	26005	Derrycahill	Suck	1085.4	1054	0.56	0.708	0.359

Table 5-13 Final selected stations for inclusion in River Suck pooling group

Rank	Station	Name	River	AM years	l-cv	l-cg	l-ck	
1	26007	Bellagill	Suck	68	0.135	0.201	0.236	
2	16008	Newbridge	Suir	65	0.095	0.121	0.168	
~~3~~	~~16009~~	~~Cahir~~	~~Suir~~	~~66~~	~~0.094~~	~~-0.081~~	~~0.053~~	~~reject~~
4	36010	Butler's Bridge	Annalee	64	0.145	0.233	0.213	
5	26002	Rockwood	Suck	68	0.105	0.217	0.253	
6	30004	Corofin	Clare	55	0.143	0.308	0.253	

Rank	Station	Name	River	AM years	l-cv	l-cg	l-ck	
7	16011	Clonmel	Suir	47	0.146	0.110	0.055	
8	15002	St. John's	Nore	43	0.189	0.117	0.159	
9	26005	Derrycahill	Suck	66	0.111	0.171	0.259	
		Combined		***476***	**0.134**	**0.185**	**0.1995**	

The pooled Growth curve for EV1, GEV and GLO based on a pooling group average l-moments is presented below in Table 5-14.

Table 5-14 Pooled Growth Factors X_T from selected 8 station Pooling group

Return Period T	EV1	GEV	GLO
5	1.000	1.000	1.000
10	1.228	1.229	1.208
25	1.379	1.383	1.357
50	1.570	1.583	1.569
100	1.711	1.734	1.750
200	1.851	1.886	1.953
500	1.991	2.040	2.182
1000	2.176	2.247	2.533

Of concern in respect to the above-pooled analysis is the potential for underestimating the return period floods in the River Suck at Ballinasloe, particularly as the largest individual growth curve within the pooling group is the Bellagill station (just upstream of Ballinasloe) and the significant scatter present in the individual pooling group growth factors particularly at the larger return period floods, refer to Figure 5-24 to Figure 5-26. These figures suggest that the homogeneity assumption is not met and that the selected pooling group represents samples from different parent populations. The 100year growth factor is of the order of 1.75, giving a 100year return period flood estimate at Bellagill of 164cumec which is significantly exceeded both in 2009 and 2015 which would be of concern if such flood magnitude was chosen as the 100year design flood on which to base the flood defenses. This potential for underestimation of the Growth factors is addressed latter by including the addition of the statistical standard error.

5.4.3 Associated Standard Error of Pooled X_T

The concept of pooled analysis hinges on the group representing a single parent distribution with the pooled stations representing independent samples of this distribution, and therefore, such added sampling of the population of floods reduces the statistical standard error over a single station analysis.

To examine the effect of statistical error and the impact of the pooling group size a Monte-Carlo simulation was performed. In this simulation, the parent statistics were set to the pooled average L-cv and L-skewness values of 0.134 and 0.195, respectively and the sample size set to the average of 59AM years per station.

Simulations were performed with 1 station, 4 stations and 8 stations and the percentage standard errors calculated for each of these simulations. Refer to Table 5-15 for calculated percentage errors associated with 1, 4 and 8 gauges representing samples from the parent population. The associated statistical error reduces by a factor of 3 for 8 stations over a single site analysis, but inherent in this reduction is that the standardized (divided by the respective

QMED's) AM series from all eight stations originate from a single parent distribution (homogeneity) which is unlikely to be the case. To demonstrate the assumption of homogeneity on the standard error the eight station pooling group is used in the following Figure 5-24 to Figure 5-26. The 67-percentile confidence interval upper and lower is the addition and subtraction of standard error.

It is clear, based on the computed confidence interval presented in Figure 5-24 to Figure 5-26 that the pooling group does not represent a homogenous group of stations and that the EV1 particularly does not well represent this group. The computed pooled standard error is extremely small for the EV1 and only valid if all of the data were from the same parent which is certainly not likely to be the case based on Figure 5-24. The other distributions of the GEV and GLO only feature moderately better and actual statistical error is likely to be significantly larger than the computed statistical error as a result of the lack of homogeneity in the data, refer to Figure 5-25 to Figure 5-26 for the GEV and GLO fit to eight station pooling group data.

Table 5-15 Computed Percentage Statistical Standard Error associated with a different number of gauges within the pooling group.

Return Period T	GLO			GEV			EV1		
	m=1	m=4	m=8	m=1	m=4	m=8	m=1	m=4	m=8
10	4.6	2.4	1.7	4.04	2.07	1.5	2.91	1.47	1.04
100	15.3	7.5	5.4	12.56	6.35	4.4	4.86	2.46	1.74
1000	34.0	15.0	10.7	25.46	12.06	8.4	5.99	3.04	2.15

Note : *m is number of stations, N is the average number of AM years per gauge = 59 and Parent L-Cv = 0.135 and parent L-skew = 0.201*

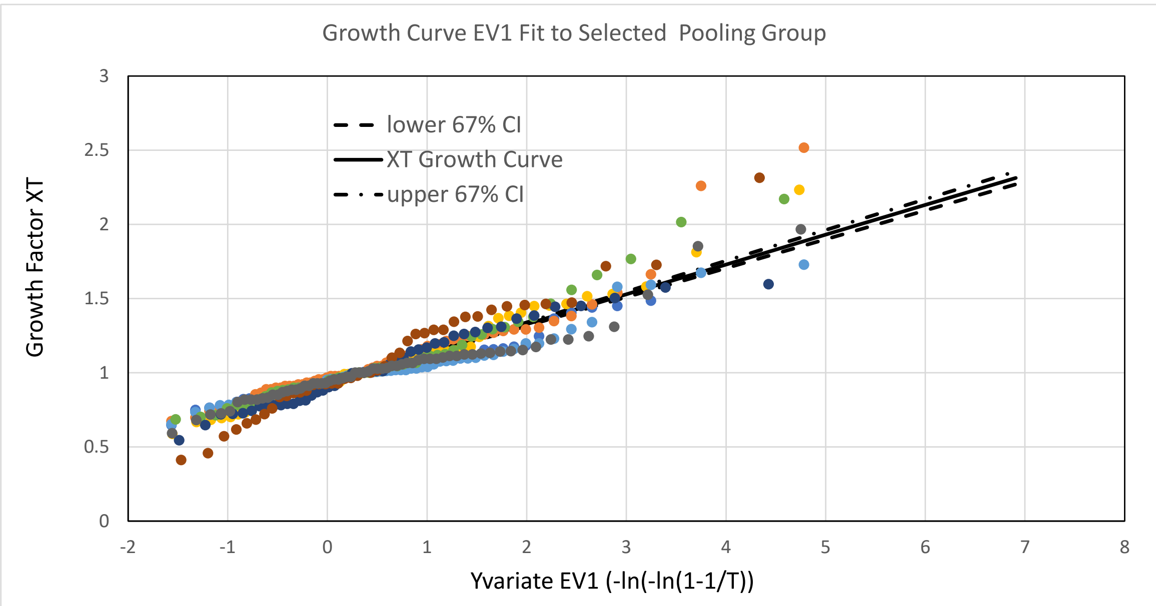

Figure 5-24 Flood Growth Curves based on EV1 fit of eight station pooling group including upper and lower Confidence Intervals based on assumption that all stations are from a single parent distribution (

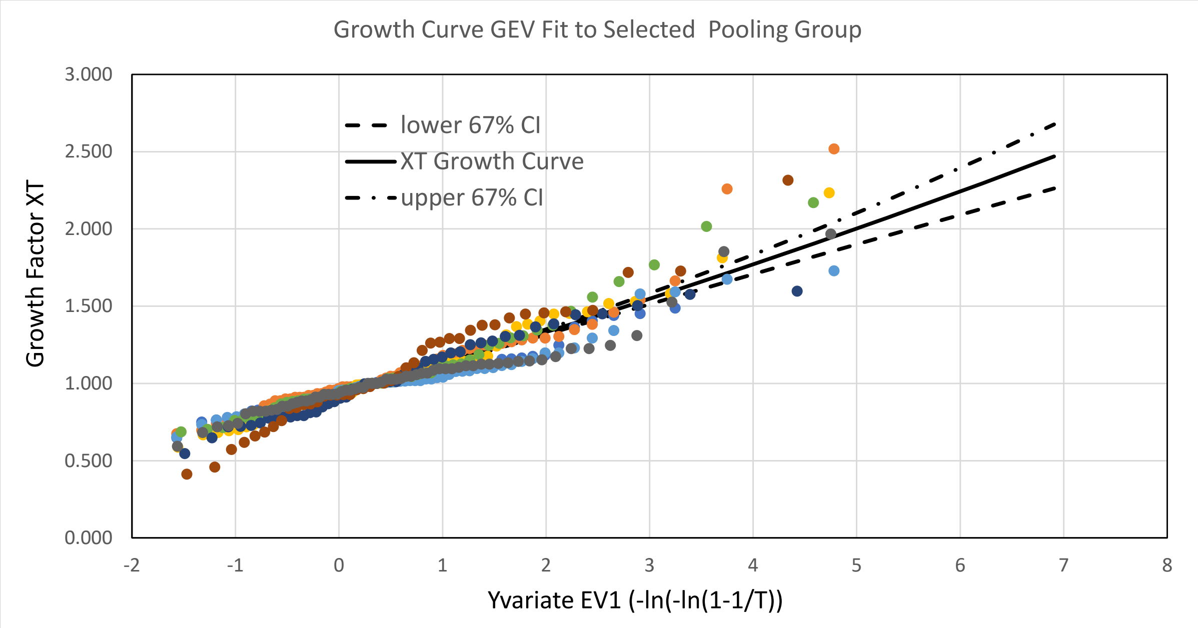

Figure 5-25 **Flood Growth Curve based on GEV fit of eight station pooling group including upper and lower Confidence Intervals based on assumption that all stations are from a single parent distribution**

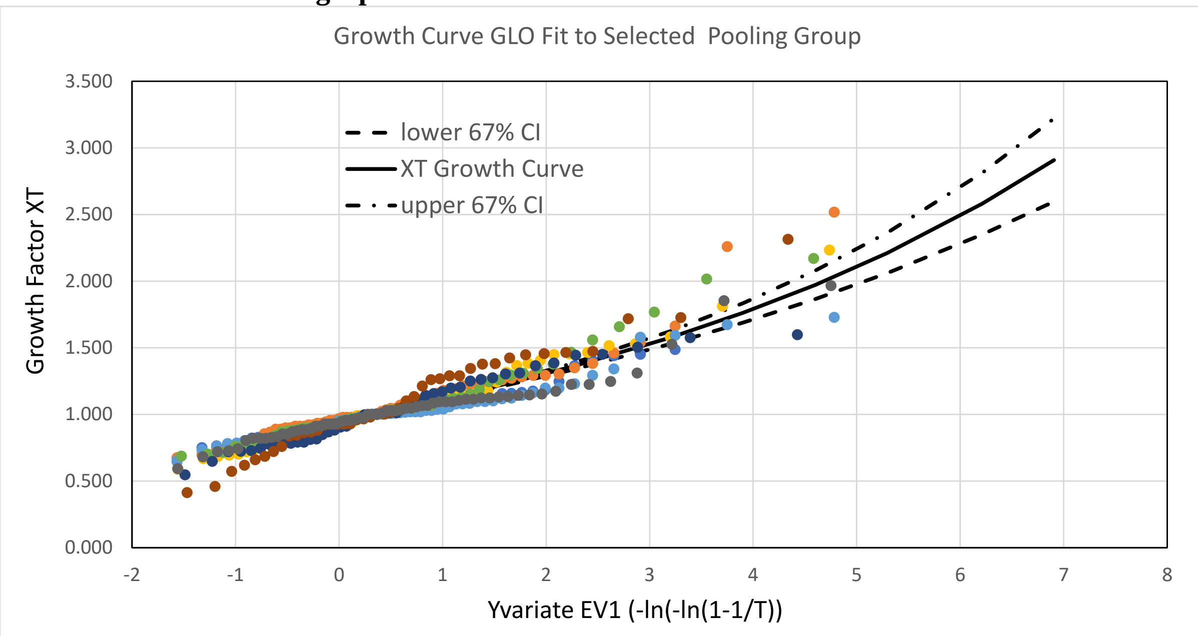

Figure 5-26 **Flood Growth Curves based on GLO fit of eight station pooling group including upper and lower Confidence Intervals based on assumption that all stations are from a single parent distribution.**

Clearly based on the degree of scatter in above Figure 5-24 to Figure 5-26 this assumption of homogeneity is not satisfied and the actual 67-percentile CI's are likely to be much wider.

A more realistic measure of the relative standard error of the Pooling Group Growth Factors is to base the standard error estimate on the single averaged site with the pooled average L-moments and the mean station sample number which for the pooled group of 8 stations is l-cv = 0.134 and l-skewness = 0.185 and mean sample number N = 59. The estimated standard error of the fitted EV1, GEV and GLO distributions are presented in Figure 5-27 to Figure 5-29.

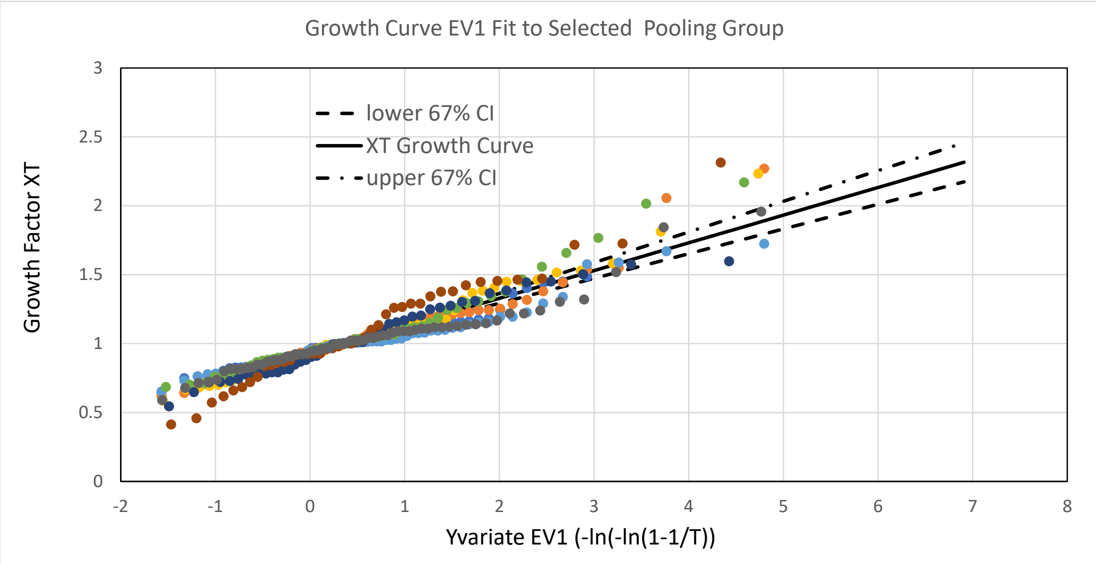

Figure 5-27 Flood Growth Curves based on EV1 fit of 8 station pooling group with 67-percentile confidence Interval based on the average S.E.

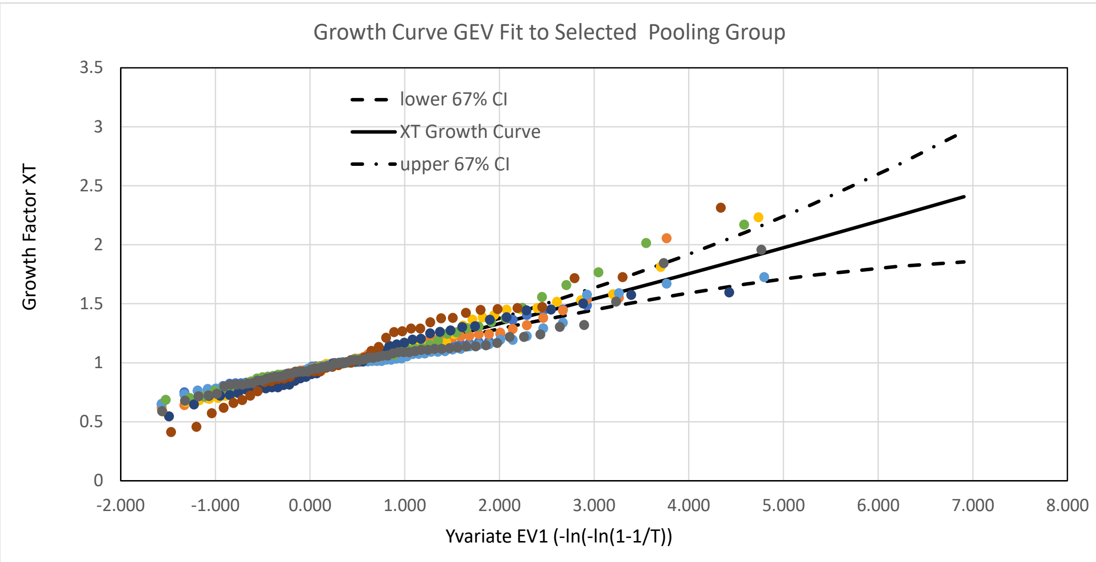

Figure 5-28 Flood Growth Curve based on GEV fit of 8 station pooling group with 67-percentile confidence interval based on the average S.E.

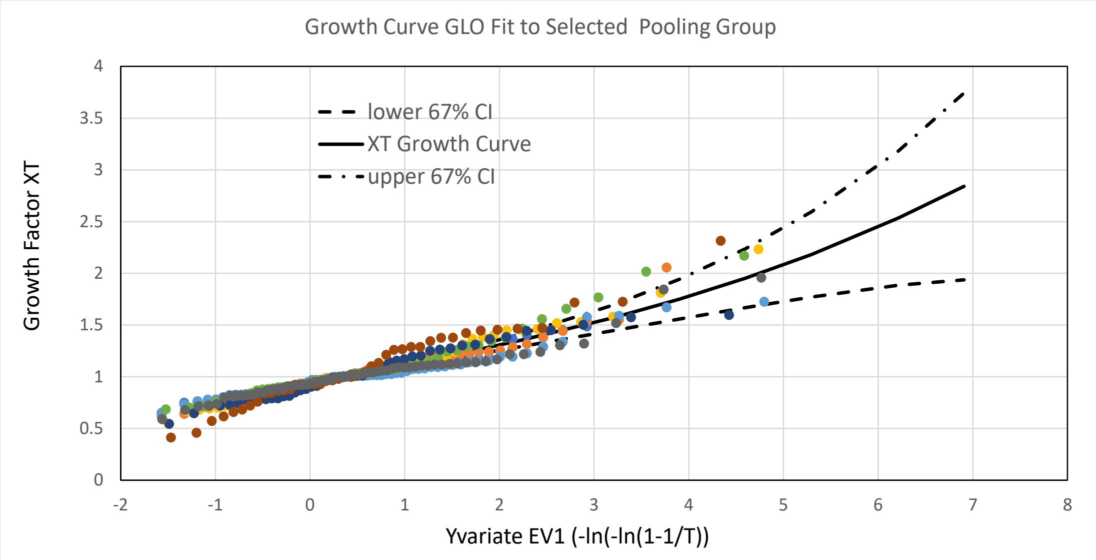

Figure 5-29 Flood Growth Curves based on GLO fit of 8 station pooling group with 67-percentile confidence interval based on the average S.E.

The estimated relative standard error for the Suck 4-gauges geographical pooling Group and the FSU 8 gauges pooling group for the EV1, GEV and GLO distributions are presented below in Table 5-16.

Table 5-16 Computed Percentage Relative Standard Error associated with the selected pooling groups.

Return Period T	EV1 % Standard Error		GEV % Standard Error		GLO % Standard Error	
	Pooled[1]	Pooled[2]	Pooled[1]	Pooled[2]	Pooled[1]	Pooled[2]
5	1.86	2.00	2.19	2.16	2.50	2.49
10	2.74	2.95	4.13	3.89	4.77	4.57
25	3.61	3.90	7.36	6.59	8.58	7.90
50	4.13	4.47	10.34	8.98	12.21	11.00
100	4.56	4.95	13.82	11.66	16.62	14.62
200	4.93	5.36	17.85	14.65	21.96	18.89
500	5.35	5.82	24.17	19.15	30.92	25.61
1000	5.62	6.12	29.92	22.96	39.49	31.78

Pooled[1] is the 4 geographical pool of River Suck Gauges
Pooled[2] is the 8 Gauge pooling group from hydrologically similar catchments

5.4.4 Recommended Flood Growth Factors

The recommended statistical distribution for the River Suck and its tributaries is the GLO distribution, as it represents the best fit to the recorded annual maximum flood flow series for the River Suck at its four gauging stations. It consistently provided higher extreme flood flows over the other statistical distributions considered, which in view of the extreme nature of the recent 2009 and 2015 flood events is preferable. The GLO distribution suffers less from being upper-bounded when fitted to the AM data over the GEV. The EV1 2 -parameter distribution did not fit well the at-site Bellagill AM data or the pooling groups data and was therefore not considered appropriate for this study. It should be noted that EV1 distribution is generally considered a good fit for Irish gauged catchments (FSU 2011).

At-site and pooled statistical analyses were carried out to estimate the flood growth curve for the Suck fitting the preferred GLO distribution and the results are summarized below in Table 5-17.

The FSU pooling group method provided 8 gauged stations for inclusion as a pooling group, but when the statistical moments and standardised AM data was considered, it showed the group not to be very homogenous with wide scatter and the pooling only producing an averaging of these stations and predictions for the 100year significantly less than the observed Nov 2009 flow at Bellagill. Table 5-17 below summarises the return period flood growth factor and estimated statistical error for both pooling group options (catchment based 4 station group and 8 station hydrologically similar group).

Table 5-17 Computed Flood Growth Factors based on the recommended GLO Distribution along with the computed statistical standard error at Bellagill

Return Period T	Growth Factor At-Site	% S.E. At-Site	Growth Factor Pooled[1]	% S.E. Pooled[1]	Growth Factor Pooled[2]	% S.E. Pooled[2]
5	1.23	2.66	1.21	2.50	1.21	2.49
10	1.41	5.18	1.38	4.77	1.36	4.57
25	1.60	9.52	1.63	8.58	1.58	7.90
50	1.88	13.76	1.86	12.21	1.76	11.00
100	2.12	19.01	2.13	16.62	1.97	14.62
200	2.38	25.40	2.45	21.96	2.21	18.89
500	2.78	36.20	2.98	30.92	2.58	25.61
1000	3.13	46.69	3.47	39.49	2.91	31.78

Pooled[1] is the 4 geographical pool of River Suck Gauges
Pooled[2] is the 8 Gauge pooling group from hydrologically similar catchments
At-Site represents the Bellagill single site Statistical Analysis

The OPW FSU method (FSU 2009) provides the option for a combination of the pooled and at Site Growth Curve under different circumstances. In the case of the Ballinasloe Study, it is recommended that a combination of the at-site Bellagill growth curve and the pooled growth curve from the four Suck gauges be used for this study. This approach provides 40% weighting to the Bellagill gauge (nearest to the study area) and 20% weighting to the other three in estimating the flood growth curve. This also limits the impact of the Willsbrook gauge growth curve, which generates the steepest growth curve and has the smallest catchment area and correspondingly the poorest hydrological similarity to the study area. This combination also applies to the estimated statistical standard error of growth curve ordinates. The recommend growth curve and associated percentage standard error is presented below in Table 5-18 and Figure 5-30.

Table 5-18 Recommended Growth Factor and statistical error for the River Suck and its tributaries

Return Period T years	Growth Factor X_T	Percentage Standard Error
5	1.22	2.58
10	1.40	4.98
25	1.62	9.05
50	1.87	12.99
100	2.13	17.82
200	2.42	23.68
500	2.88	33.56
1000	3.30	43.09

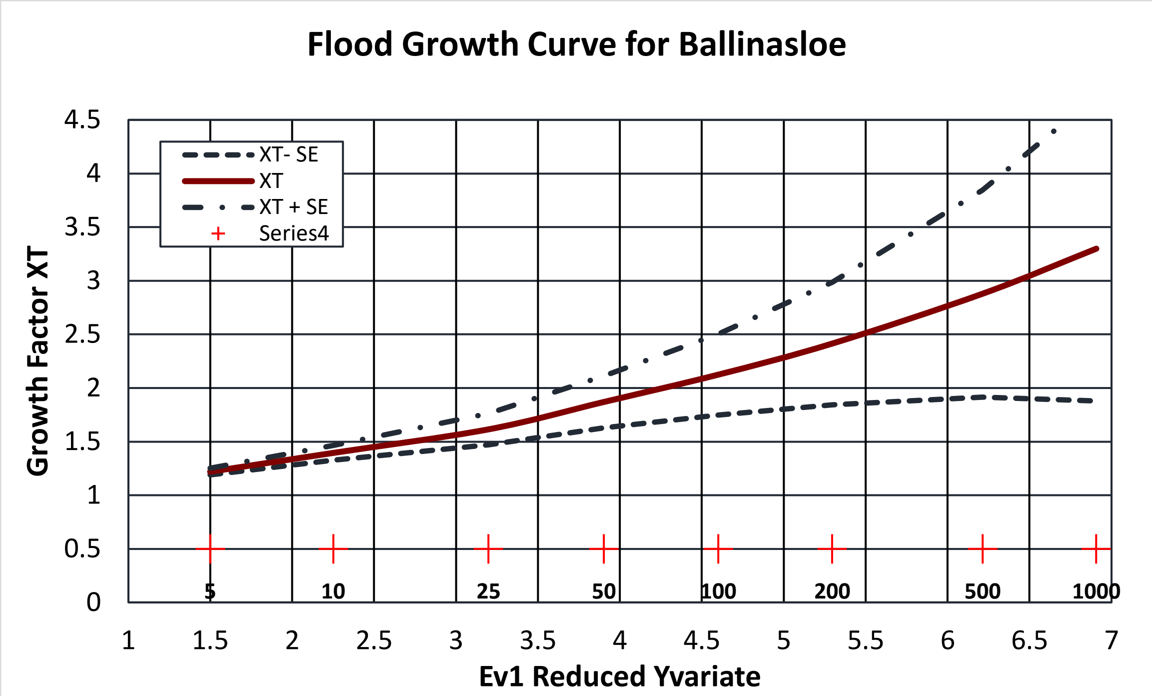

Figure 5-30 Recommended Flood Growth Curve for River Suck and its tributaries at Ballinasloe with 67% statistical confidence intervals included.

The use of pooling groups for other tributaries with different hydrological characteristics within the study area suffer the same problem of lack of homogeneity in the gauged AM data and an averaging effect with a tendency possibly to under predict the growth factors at the more extreme events. Therefore it is recommended that the estimated River Suck flood Growth curve in Table 5-18 be used on all tributaries within the study area independent of size and similarity.

For all tributaries that rely on the FSU index flood (QMED) calculation the above single regional growth curve is recommended. For the very small urbanised catchments that rely on the rational method with storm rainfall the return period flows will be determined from the rainfall statistics provided by the FSU Web portal method.

5.5 FSU Index Flood Method Estimates at HEP's

The Flood Studies Update (FSU) index flood method will be applied to all hydrological estimation points at the HEPs within the study area. This method sets the index flood as the annual median flood (2year return period) QMED based on the FSU regression equation derived for a number of key physical catchment descriptors (PCDs) of its contributing catchment. This regression equation which uses several PCDs, has a factorial standard error of 1.37 and is presented below in equation (10) for a rural catchment. To include for urbanization effects the adjustment factor from equation (11) is applied.

To improve the reliability of the FSU flood estimation equation, a gauged pivotal site can be selected, which provides an adjustment for the PCD flood estimate.

The return period estimates can then be determined by multiplying the QMED estimate by suitable flood growth factors XT derived either from at-site analysis or from the pooled analysis of selected gauging stations. In the case of the mainline River Suck at Ballinasloe, the selected pivotal site for adjustment of the QMED estimate will be the Bellagill gauge.

FSU PCD ungauged flood estimation equation

$$Qmed_{rural} = 1.237 \times 10^{-5} * AREA^{0.937} * BFISOIL^{-0.922} * SAAR^{1.306} * FARL^{2.217} * DRAIND^{0.341} * S1085^{0.185} * (1 + ARTDRAIN2)^{0.408} \quad (10)$$

$$Qmed = (1 + URBEXT)^{1.482} * Qmed_{rural} \quad (11)$$

An issue with the FSU method on the OPW Web FSU Web portal is that it is based on flood data only up to 2004/2005 and does not include data from 2006 onwards, which is 16 years of flood data not included (also this period was the wettest period on record for west of Ireland catchments). Such updated data has been included in this study in terms of including up to date AM series for all pooling station and pivotal QMED sites considered.

Another issue with the current FSU method is its over-reliance on a single pivotal site, particularly for ungauged catchments sites that are remote from the selected pivotal site and can lead to significant uncertainty and error if the pivotal gauge site does not meet the homogeneity rule with respect to the subject site and where the AM series and flow ratings are not very reliable.

The OPW Hydrology section at Trim have developed a QMED Atlas based on adjusting the PCD estimate using a combination of multiple sites that are hydrologically similar. This method is still under development by the OPW, and it relies on combining a weighted adjustment of a large number (20 in total) of hydrologically similar gauged sites. This method has been tested by the OPW and found to be generally more reliable than the use of a single pivotal site. These QMED estimates for the Suck Catchment have been provided by the OPW for comparison with the computed adjustments. However, the at site data was used in preference to the OPW QMED Atlas estimates as the QMED atlas is only in development stage and does not include the most up to date AMAX gauged series. Furthermore, the use of the Bellagill as a pivotal site allowed inclusion of the statistical error of the gauged data to cater for a degree of uncertainty

The adopted approach is to use the reviewed Bellagill gauged site, given its proximity and reliability as the pivotal site to adjust the QMED estimates at all HEPs along the mainline of the River Suck and on the larger tributaries(i.e. Bunowen, Deerpark and Bellinure). The Bellagill pivotal Site is based on a 68year AM record which provides a QMED of 93.6cumec with a statistical standard error of 3.81cumec (c. 4.3% standard error). The calculated adjustment factor is small at 1.012, A further review of the QMED estimate taking trend and uncertainty into account is presented in Sections 7 and 10 and the final pivotal adjustment factor for Bellagill increases to 1.173. The same approach is adopted for the larger tributary rivers of the Bunowen, Deerpark and Bellinure River with Bellagill as the pivotal site and the return period estimates based on the Suck Catchment Growth factor presented earlier in Section 5.4.

It should be noted here in respect to the QMED estimates and its standard error that QMED values will be adjusted to cater for increasing trend latter in Section 7 with the final recommended QMED values and the return period design flows QT's at all of the HEP's presented latter in section 11.

5.6 Flood Estimates on Smaller Tributaries at Ballinasloe

The IH124 (1994) equation for small ungauged catchments is still one of the methods of choice in Ireland today even though it relies on the 1975 FSR catchment characteristic mapping and is derived from UK small catchments only. The FSU provides a small ungauged flood estimation equation but is not currently considered sufficiently reliable for small catchment to be promoted as the method of choice over other methods. Other such favoured methods for very small catchments is the Rational Method based on runoff coefficients and return period rainfall intensities.

There are a number of smaller tributaries that feed the River Suck within the study area at Ballinasloe. The PCDs for these tributaries are presented below in Table 5-19.

Table 5-19 FSUPCDs estimates for the Smaller Tributaries within the Ballinasloe study area

water_body	node_id	AREA	SAAR	FARL	BFISOIL	DrainD	S1085	ART DRAIN2	URB EXT
Cuilleen	26_936_3	13.3	932.1	1	0.609	1.282	3.196	0	0
Pollboy26	26_3033_5	2.8	920.4	1	0.713	0.741	5.307	0	0.073
Loughbown	26_3824_10	8.4	961.5	1	0.738	0.709	3.398	0	0.0403
Culliaghbeg	26_3624_7	10.4	914.3	1	0.737	0.742	2.551	0	0
Laurencetown	26_3065_3	20.8	944.9	1	0.692	0.949	3.953	0	0.0225

The FSU in Work Package 4.2 examined flood estimation in small and urbanised catchments (OPW 2012) and found for a relatively limited data set of gauged Irish catchments a set of 41 stations of less than 30km^2 in area and minimum record length of 7years were available. Removing six outlier stations left 35 stations for analysis and comparison of the various estimation methods. The FSU (3 variable) performed slightly better than the FSSR (3 variable) and the IH124 (3 variable) equations. The computed factorial standard errors for the 35 station data set (catchment areas 2.8 to 28.6km^2) were found to be 2.06, 1.96 and 1.93, respectively. A revised FSU, 5 variable equation which in addition to SAAR, BFISoil, and AREA, included FARL and S1085 was developed by regression of the 35 station dataset giving a FSE 1.686. A degree of caution should be applied when using this FSU 4.2 equation as a choice over the other methods as this equation was specifically developed for the 35stations and thus would be expected to produce the best performance in term of statistical error over the other methods which were derived from other and larger data sets.

A summary of the results applied to the Ballinasloe small tributaries are presented below in Table 5-20. The available pivotal sites for these small streams from the FSU web portal method is not geographically or hydrologically very compatible with subject sites and, therefore, no adjustment factor has been included.

Table 5-20 QMED estimates for the Smaller Tributaries within the study area using various ungauged estimation equations at confluences with the Suck

water_body	node_id	FSU (7 variable)	FSU (3 variable)	FSU 4.2a (5 variable)	FSSR (3 variable	IH124 (3 variable)
Cuilleen	26_936_3	2.256	0.559	1.157	2.566	2.249
Pollboy26	26_3033_5	0.452	0.216	0.393	0.642	0.590
Loughbown	26_3824_10	1.119	0.560	1.007	1.804	1.600
Culliaghbeg	26_3624_7	1.167	0.602	1.010	1.999	1.767
Laurencetown	26_3065_3	3.010	1.030	2.174	3.933	3.399

Note SOIL factor = 0.3 and QMED = 0.95*QBAR for the IH124 and FSSR equations.

The FSU methods, particularly the FSU 3 variable and the FSU 4.2 equations, produce significantly lower estimates than the FSU full 7 variable equations, the FSSR and the IH124 3 variable equations. The FSU and IH124 estimates are reasonably similar and given the continued popularity and experience in applying the IH124 equation, it is the recommended flood flow estimation method for the small tributary catchments discharging to the Suck river within the Ballinasloe study area. It should be noted that the factorial error of the method fitted to its original 89 small gauged British catchments is 1.65 and for the 35 Irish catchments, a factorial standard error of 1.93 was obtained.

6 Joint Probability Analysis

6.1 Introduction

In order to estimate the contributions from the various tributaries within the scheme area to the River Suck at the design return periods dependance modelling was carried out using joint probability analysis for the limited gauged data where available and using the FSU dependance model from Work Package 3.4 (OPW,2010).

6.2 Gauged JPA analysis

6.2.1 Bunowen River

There are no hydrometric stations with flood flow estimates present on any of the relevant River Suck tributaries to Ballinasloe. The only hydrometric station present is on the Bunowen at Ahascragh Pump Station (26140) which only provides water level with no available high flow rating for this station. This station is in service since 2007 and provides a 12 year record length. The annual maximum flood level series was extracted from the Ahascragh gauge (12 years of AM for comparison with the River Suck Bellagill (nearest to the Study area) gauged AM flows. Of the 12 AMAX years, 8 of the floods coincided with the same flood event as on the River Suck, but generally, the Bunowen peaked c. 40hours earlier. The largest flood at Ahascragh was the December 2015 event followed by the November 2009 flood event. These were also the highest recorded floods on the River Suck over its 68year record period, except in reverse order. This would suggest that similar return period flood events possibly apply to the Bunowen and the Suck originating from the same rainfall events with hydrograph shape and storage attenuation in the downstream floodplain important in their joint combination.

The Bunowen catchment being smaller and quicker, was found typically to peak almost 40hours earlier than the River Suck. With only 12 years of AM data for Ahascragh, the estimated return period flood levels from frequency analysis will not be very accurate and susceptible to large sampling error. Using the same 12 years for the Suck at Bellagill a relationship between return periods was obtained; refer to Figure 6-1 and Table 6-1 below. It was found that there was poor correlation in return periods due to the sample size.

From this analysis, the following dependance relationship was obtained between the Bunowen Peak Flood Flow (which generally peaks 40hours earlier) and the resultant flood flow in the River Suck.

Table 6-1 Computed Return period relationship in downstream River Suck (at Bellagill) and range of design return period floods in the Bunowen River.

Return Period Bunowen River T (years)	2	5	10	20	50	100	200	1000
Return Period River Suck T (years)	1.4	2.2	3.1	4.3	6.6	9.2	12.7	27.4

In reverse, when the River Suck peaks, the Bunowen at the Ahascragh gauge is into its second day of recession and the flow magnitude was found to be below 2 year return period for the 12 year record length, with the majority of events at or less than 1year return period with no consistent trend.

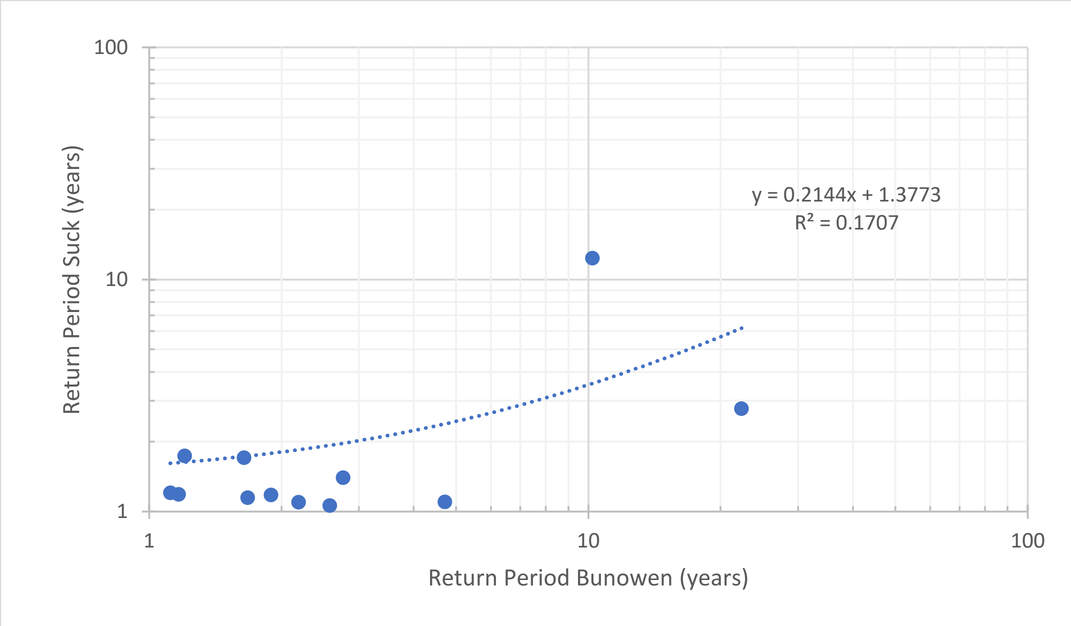

Figure 6-1 Period Relationship between Bunowen Flood Peak and River Suck Flood Flow (there is poor correlation with a coefficient of determination R2 = 0.171)

6.2.2 Shannonbridge Gauge

A joint probability analysis was carried out between the downstream flood levels in the River Shannon at Shannonbridge gauge (located 1km upstream of the Suck-Shannon confluence) and the River Suck Bellagill Gauge. The following return period relationship in Table 6-2 was obtained from the AM series at the two stations:

Table 6-2 Computed Return period relationship between downstream River Shannon water levels (at Shannonbridge) and design return periods in the River Suck at Bellagill.

Return Period River Suck T (years)	2	5	10	20	50	100	200	1000
Return Period River Shannon T years	1.5	4.9	7.3	9.8	13.0	15.5	18.0	24.0

This analysis shows that the flood peak magnitudes in the River Suck and Shannon reasonably coincide in terms of magnitude for the higher frequency (i.e. lower return period) events up to almost 10 year return period, but for the larger return periods of 100 and 1000 in the Suck at Ballinasloe, the River Shannon does not reach its peak with critical combined probability for 100year flood event at Ballinasloe being produced by 100year in the River Suck and 15year return period flood level downstream in the River Shannon at Shannonbridge. The 1000year event on Suck combines with a 24 year return period flood level in the River Shannon.

6.3 Flood Studies Update 3.4 method

As part of the FSU flood studies a guidance was developed for river basin modelling and the dividing the basin into model reaches and setting the design inputs between tributaries and the main river reach. This guidance was based on fitting marginal flood frequency distributions and a model of inter-site dependence using 166 gauging stations from the FSU gauged database (OPW, 2010).

A summary of the dependence model results between the inflow and the main river reach giving recommended percentage return period flow contributions for a range of design return period flows in the Main River (i.e. River Suck) is presented in Table 6-5 below for the Bunowen and Deerpark and would also apply to the inflows from the smaller tributaries at Ballinasloe.

Table 6-3 Summary of FSU 3.4 Dependance Model giving recommended return period of inflow for a range of design return periods in the receiving main river

			Design Return Period in Main River downstream of confluence							
centroids within 25km^2	**Ratio of Areas within a factor of 2.7**	**Difference of FARL <**	**2**	**5**	**10**	**20**	**50**	**100**	**200**	**1000**
FALSE	FALSE	TRUE	1.1	1.3	1.5	2.0	2.9	4.0	5.9	12.5
FALSE	TRUE	FALSE	1.1	1.59	2.0	2.6	3.8	5.3	7.1	14.3
FALSE	TRUE	TRUE	1.7	3.4	6.7	13	33	50	100	500
TRUE	FALSE	FALSE	1.4	2.4	3.8	6.3	14	25	50	200
TRUE	FALSE	TRUE	1.4	2.2	2.9	4.3	10	17	25	100
TRUE	TRUE	FALSE	1.8	2.9	4.3	6.7	13	20	33	143
TRUE	TRUE	TRUE	1.8	3.3	5.9	11	25	50	100	333

Note BFISOILS of the two catchments are within 0.3

Table 6-4 Input Data To FSU WP 3.4 Dependance Model for Bunowen and Deerpark flood inflows to River Suck

	cente	centn	AREA	FARL	BFI
Bunowen	173600	237990	136.73	0.9999	0.628
Suck	174320	259900	1362	0.984	0.5963
		21.922	9.961	0.016	0.032
		TRUE	FALSE	TRUE	TRUE
	cente	centn	AREA	FARL	BFI
Deerpark	177740	231750	61.6	0.994	0.642
Suck	174320	259900	1424.4	0.984	0.598
		28.357	23.123	0.010	0.044
		FALSE	FALSE	TRUE	TRUE

Table 6-5 Dependance model estimates of return period(years) for Bunowen and Deerpark Rivers coinciding with the design period periods for the River Suck (FSU 3.4 Dependence Model)

Tributary Contribution	2	5	10	20	50	100	200	1000
Bunowen	1.4	2.2	2.9	4.3	10.0	16.4	26.3	83.3
Deerpark	1.1	1.3	1.5	2.0	2.9	4.0	5.9	13.3

Table 6-6 Estimated Bunowen and Deerpark inflow rates to River Suck from the above dependance model

Design Return Period River Suck T (years)	2	5	10	20	50	100	200	1000
Return Period in Bunowen T (years)	1.4	2.2	2.9	4.3	10.0	16.4	26.3	83.3
Bunowen QT (cumec)	17.8	20.3	21.6	23.4	27.5	30.1	32.8	40.7
Return Period in Deerpark T (years)	1.1	1.3	1.5	2.0	2.9	4.0	5.9	13.3
Deerpark QT (cumec)	8.3	9.1	9.6	10.5	11.4	12.2	13.1	15.3

6.3.1 Estimated Difference in time to peak between inflow and main river

The FSU 3.4 Guidance gives a regression equation for computing time difference between inflow tributary and the main River based on 6 PCD's as flows:

$$\text{Time\_diff} = 32.1*BFI(diff)-103*FARL(diff)+1.62*SQRT(AREA(diff)) - 1.94*TAYSLO(diff) - 46.4*ARTDRAIN(diff) - 0.0272*NETLEN(diff).$$

This equation when applied to gives a time difference of 35.4hours between the Bunowen inflow peak and the River Suck peak and a time difference of 37.5hours for the Deerpark River inflow relative to the Suck. These estimates agree well with the gauged flood level hydrographs for the Bunowen at Ahascragh and the Suck at Bellagill.

6.4 Discussion

Insufficient gauged information is available between the Bunowen River and the River Suck to allow a robust joint frequency analysis to be carried out. The results suggest that at the 100year flood in the Bunowen the return period flow in the Suck is 9years. The gauged information based on 12 years of annual maxima floods suggests a time lag between flood peaks on the Bunowen and River Suck of c. 40hours which is reasonably consistent with the estimates from the FSU WP 3.4 regression Equation of 36.4hour lag. Of the 12 AM flood events 8 were common to both the River Suck and the Bunowen and had the 2009 and 2015 floods as the largest floods. The FSU 3.4 dependance model at the 100year in the Suck gives a suggested return period in the Bunowen tributary of 16.4years and 4years in the Deerpark. There is a high degree of uncertainty in these predictions and further sensitivity analysis is required during the hydraulic modelling to assess and fine-tune the dependence relationship between the tributaries and the main river.

The combined probability analysis between the Such return period design flows and the River Shannon flood levels at Shannon Bridge near the confluence suggests that the 100year flood in the Suck combines with a 15.5year flood level in the Shannon and at the 1000year combines with a 24 year flood event. The computed lag time in flood peak between the Suck at Bellagill and the Shannon is 39 hours. The gauged data suggests typical lag times ranging from 2 to 4days between the Suck and the River Shannon.

7 Trend Analysis

7.1 Introduction

In flood frequency analysis, the underlying assumption underpinning the statistical analysis is that all observations in the data set are independent (i.e. random) and identically distributed and therefore stationary with the principle that the past is the key to the future. Such a stationarity principle is of limited validity in the era of global change which introduces much higher uncertainty in the hydrological design.

It is therefore important when dealing with maximum flood series to examine trends in the data set which can lead to the data either not being random or from the same single parent distribution and therefore not being stationary.

The causes of trend in the flood series at a particular gauge may be due to a variety of sources:

- Changes to the hydraulic regime of the river affecting flood levels at the gauge station;
- Changes to meteorological / climatological conditions;
- Changing catchment runoff characteristics for potentially (agriculture, land-use and drainage practices);
- Statistical error or variance; and
- Changes in the rating control of a station
- Changes in the weir control and operation of a managed river (i.e. such as the River Shannon which is managed by the ESB).

The following AM flood flow series stations were selected for trend analysis of their respective AM flood series:

- River Shannon at Banagher
- River Shannon at Athlone
- River Suck at Bellagill
- River Suck at Derrycahill
- River Suck at Rockmount
- River Suck at Willsbrook

7.2 Exploratory data analysis (EDA)

Exploratory data analysis (EDA) is a visual examination of the data set and forms a useful method in identifying and examining potential trends. The recorded flood flow AM records from the different gauges are examined to identify any trends (increasing or otherwise) in the QMED flow magnitude and in the coefficient of variance (CV =σ/μ (σ = population standards deviation and μ is the population mean), with the CV generally related to the flood growth curve.

7.2.1 River Shannon at Banagher

A well rated and reasonably long record of AM flows on the River Shannon is the Banagher gauge (25017) which provides 70years of AM data (1950 to 2020). The entire AM series with a 10year rolling QMED superimposed is presented in Figure 7-1 below. The figure shows considerably more flooding activity in the recent decades over the mid decades of the 60’s, 70’s and 80’s.

The catchment area of the Shannon to Banagher is large at 7980km^2 and peak floods are associated with long persistent winter rainfall events in order to fill the available storage and produce peak flows. The trends at this gauge are of relevance to the Suck at Ballinasloe. The median flood flow is 431cumec and the coefficient of variation is 0.235 for the full 70year record.

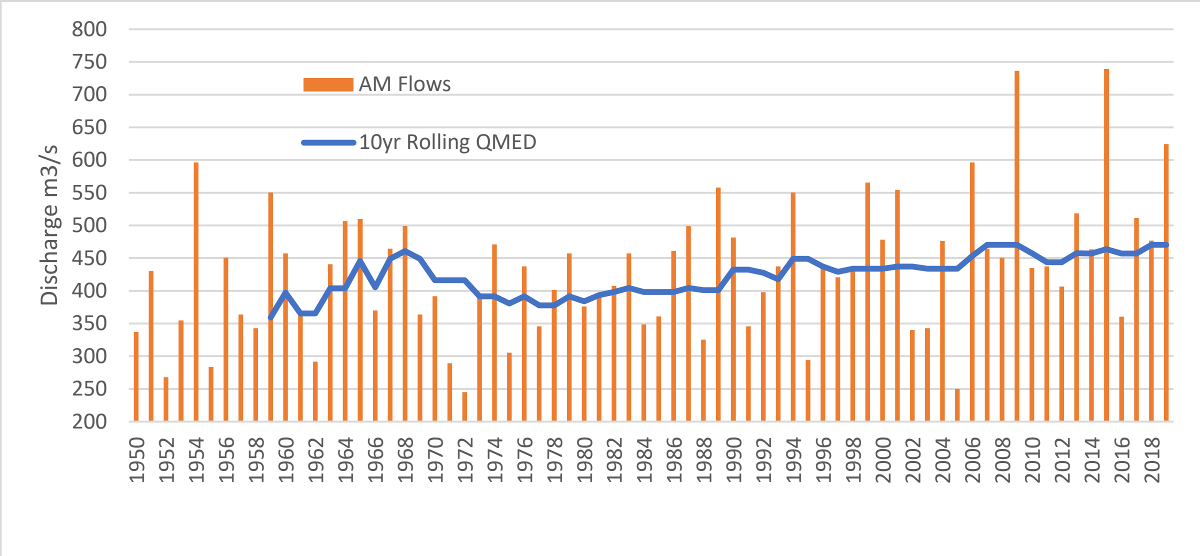

Figure 7-1 Annual Maximum flood flow series for Shannon at Banagher Station with rolling 10year QMED estimate superimposed

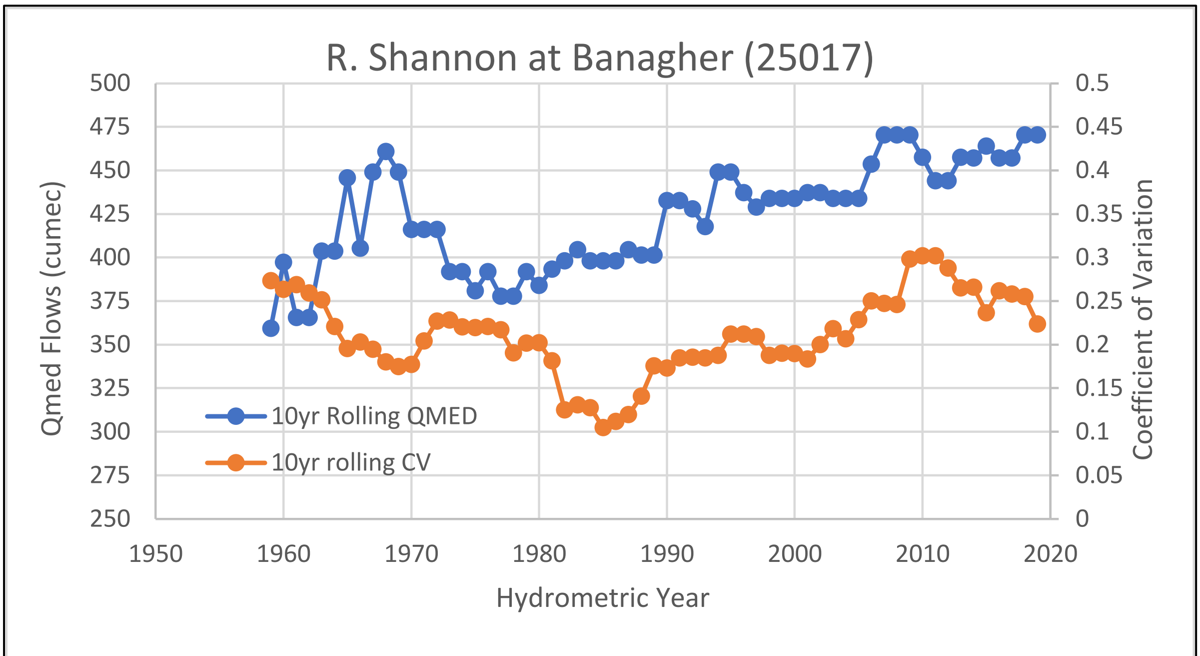

Figure 7-2 10year rolling median flood and coefficient of variation for Banagher

The Banagher gauge for the River Shannon shows that out of the 10 largest floods, 8 occurred from 1990 onwards and the remaining 2 back in the 50's (1954 and 1959). The median flood and coefficient of variation for the entire flood flow series are 431.4cumec and 0.235. The trend shows a coefficient of variation that was high for the 1950s and then declined until the end of the 1980s and steadily rose again to a peak of 0.3 and then a slight decline to c. 0.25.

Since 1990 the 10year rolling QMED has increased on average by 0.28% per annum, whereas the coefficient of variation is showing no definite trend rising and falling. Based on this information for the Shannon at Banagher it is reasonable to assume that the median flood will continue to increase by 0.28% but that the flood growth curve might remain reasonably stationary. At 0.28% compounded over 50years, this represents an increase of 15% and over 100years it represents a 32% increase in the QMED flow.

These trends on the Shannon are associated with increased rainfall amounts annually (particularly since 1990 onwards) as opposed to changes in land use or river management practices within the overall catchment.

7.2.2 River Shannon at Athlone

The River Shannon Athlone gauge provides 67years of AM series from the early 50's to date which is reasonably long to examine potential trends in flood magnitudes. The median Flood for the entire AM series is 242cumec and the coefficient of variation is 0.22, which is reasonably similar to the Banagher Gauge. The catchment area to Athlone gauge is 4601 km^2, which is 58% of the catchment area to the downstream Banagher gauge and 3.81 times the catchment area of the Suck to Bellagill gauge.

Similar to the Banagher gauge, the AM series shows wet 50's and 60's decades, dry 70's and 80 and increasingly wetter 90's, 00's and 10's. Taking the entire record, the trend of increasing QMED is apparent. The coefficient of variation has increased since 2000, which might suggest changes in the flood growth curve but is strongly influenced by a number of very large winter floods followed by a number of relatively dry winters. The QMED for the most recent two decades is 266cumec and the CV is 0.226. This represents a modest increase of 10% over the entire sample estimate and is just within the 95-percentile confidence interval of the estimate.

Similar to Banagher, this suggests an increasing trend in the QMED value with no significant trend in the coefficient of variation and thus the growth curve.

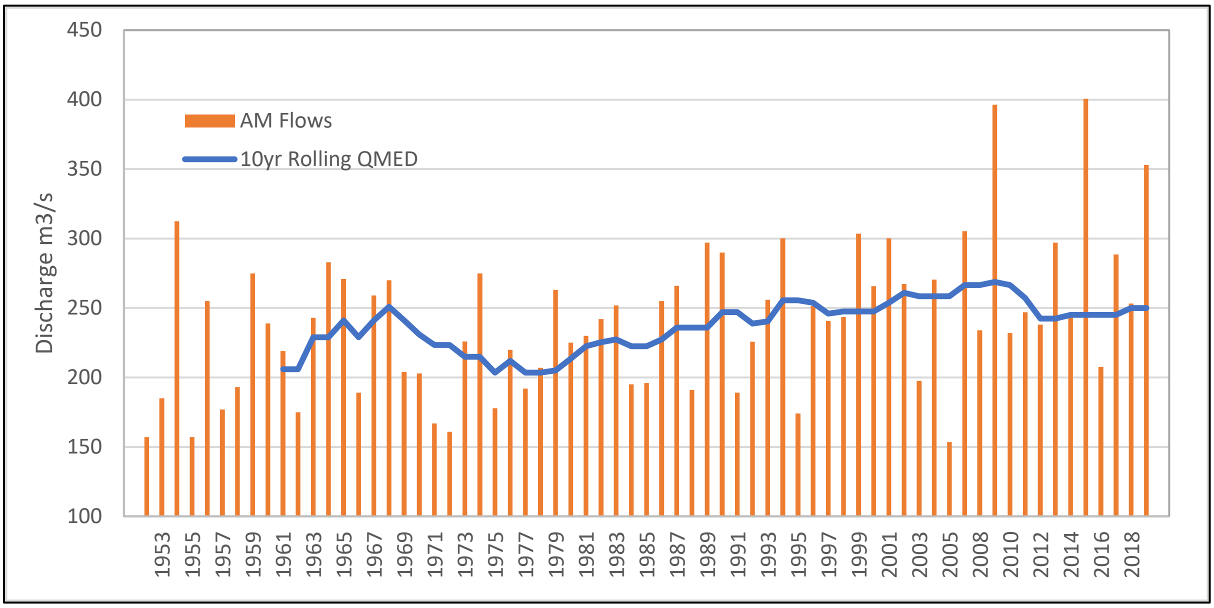

Figure 7-3 Annual Maximum flood flow series for the Shannon at Athlone with rolling 10year QMED estimate superimposed

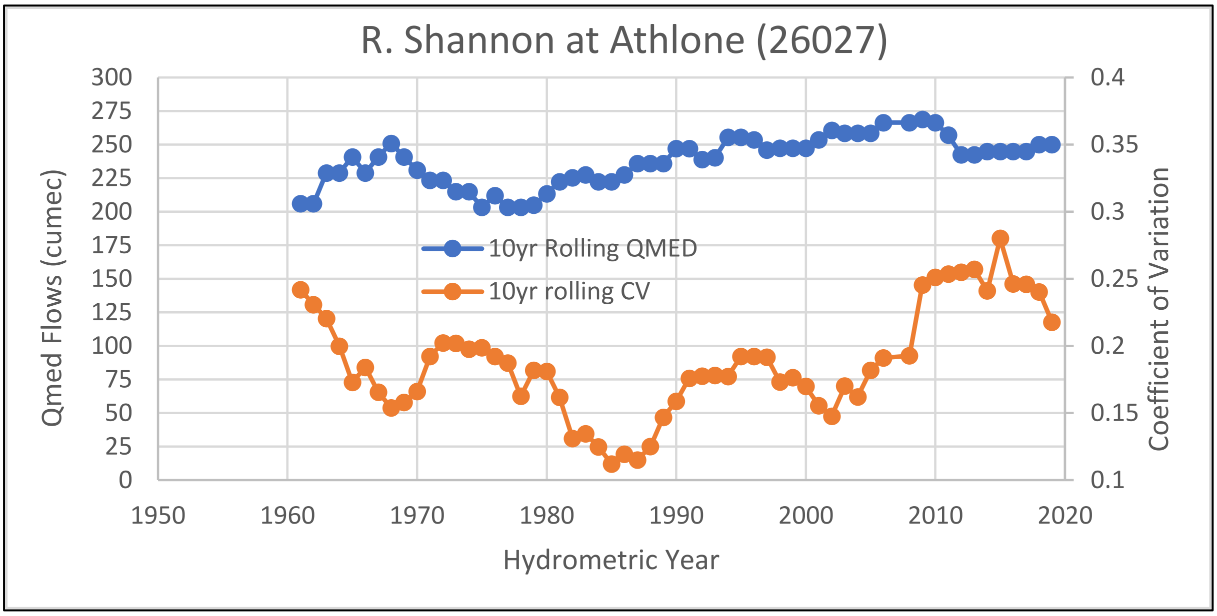

Figure 7-4 10year rolling median flood and coefficient of variation for Athlone (26027)

7.2.3 River Suck AM Flows at Bellagill

The River Suck Bellagill gauge provides 68years of AM series from the early 50's to date which is reasonably long to examine potential trends in flood magnitudes. The median Flood for the entire AM series is 93.6cumec and the coefficient of variation is 0.262 which is reasonably similar to Shannon gauges at Banagher and Athlone. The catchment area to the Bellagill gauge is 1207 km^2, which is only 15% of the catchment area to the downstream River Shannon Banagher gauge. The AM series with a 10year rolling QMED superimposed is presented in Figure 7-5 below and a 10year rolling coefficient of Variation and QMED are presented in Figure 7-6.

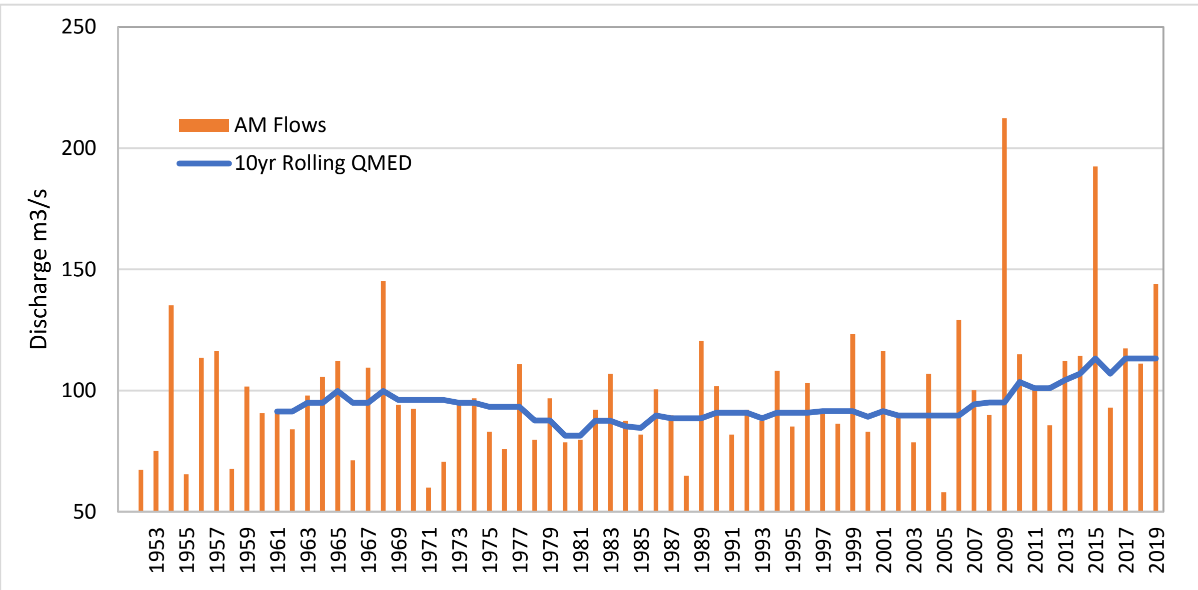

Figure 7-5 Annual Maximum flood flow series for the River Suck at Bellagill with rolling 10year QMED estimate superimposed

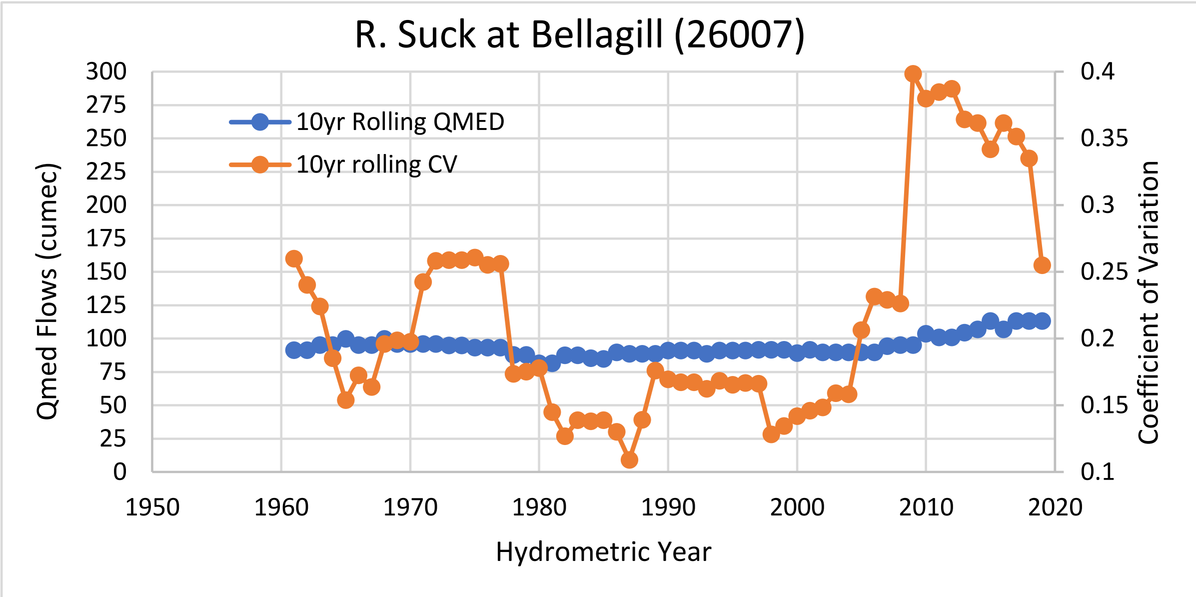

Figure 7-6 10year rolling median flood and coefficient of variation for Bellagill (26007)

Similar to the Banagher gauge, the AM series shows wetter 50’s and 60’s decades, drier 70’s and 80’s and increasingly wetter 90’s, 00’s and 10’s. Taking the entire record, the trend of increasing QMED is apparent. The coefficient of variation has increased since 2000, which might suggest changes in the flood growth curve but is strongly influenced by a number and magnitude of very large winter floods followed by a number of relatively dry winters. The QMED for the entire record is 93.6cumec and the CV is 0.226. The QMED for the most recent three decades is 101.8cumec and the CV is 0.293. This represents a modest increase of 8.8% over the entire sample estimate which is statistically significant. The QMED for the most recent 2 decades is 109cumec which is an increase of 16.5% over the entire sample QMED of 93.6cumec.

7.2.4 River Suck AM Flows at Derrycahill

The River Suck Derrycahill gauge provides 66years of AM series from the early 1954 to date which is reasonably long to examine potential trends in flood magnitudes. The median flood for the entire AM series is 89.5cumec and the coefficient of variation is 0.221 which is reasonably similar to both Bellagill and the Shannon gauges at Banagher and Athlone. The Catchment area to the Derrycahill Gauge is gauge is 1084 km^2, which is 90% of the catchment area to the downstream Bellagill gauge.

Similar to the Bellagill and Banagher gauges the AM series shows a wetter 50’s and 60’s decades, drier 70’s and 80’s and increasingly wetter 90’s, 00’s and 10’s. Taking the entire record, the trend of increasing QMED based on a rolling 10year value is somewhat apparent. The coefficient of variation is considerably higher for the wetter decades has dramatically increased since 2000, which might suggest changes in the flood growth curve but is strongly influenced by a number and magnitude of very large winter floods followed by a number of relatively dry winters. The QMED for the most recent three decades is 90.5cumec and the C_V is 0.254. This increase in QMED is only 1.1% of the entire sample QMED which is not statistically significant. The QMED for the most recent two decades is 93.45cumec and the C_V is 0.297 representing an increase in QMED of 4.4% which is well within the standard error and not considered significant. This is at variance with the Bellagill Station which showed significant increases in the QMED value based on the more recent 20 and 30year periods.

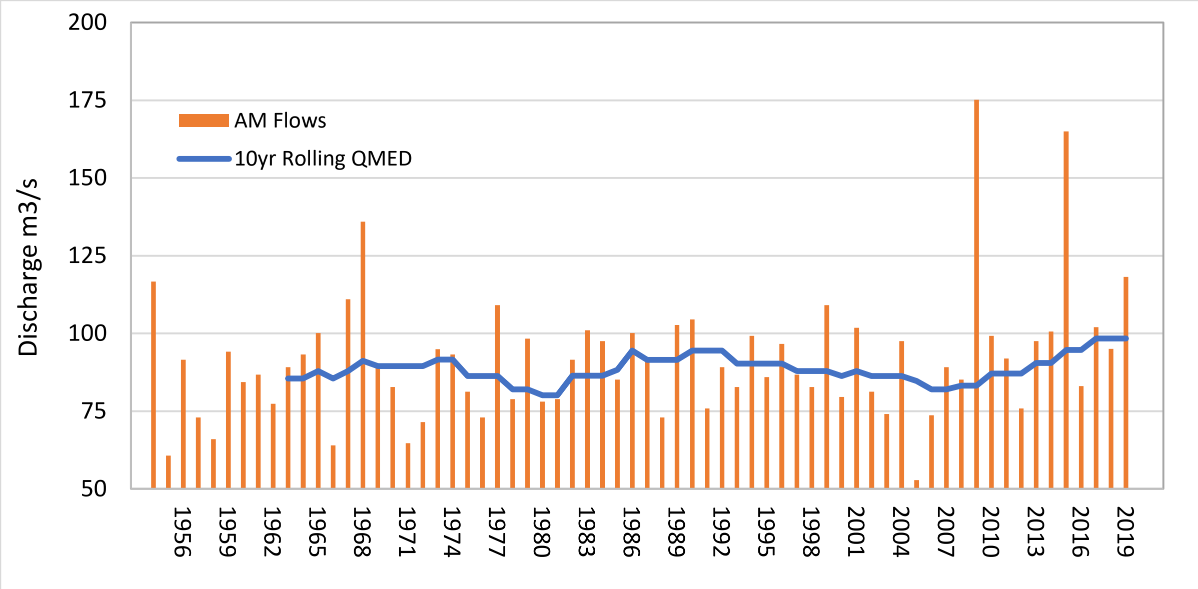

Figure 7-7 **Annual Maximum flood flow series for the River Suck at Derrycahill with rolling 10year QMED estimate superimposed**

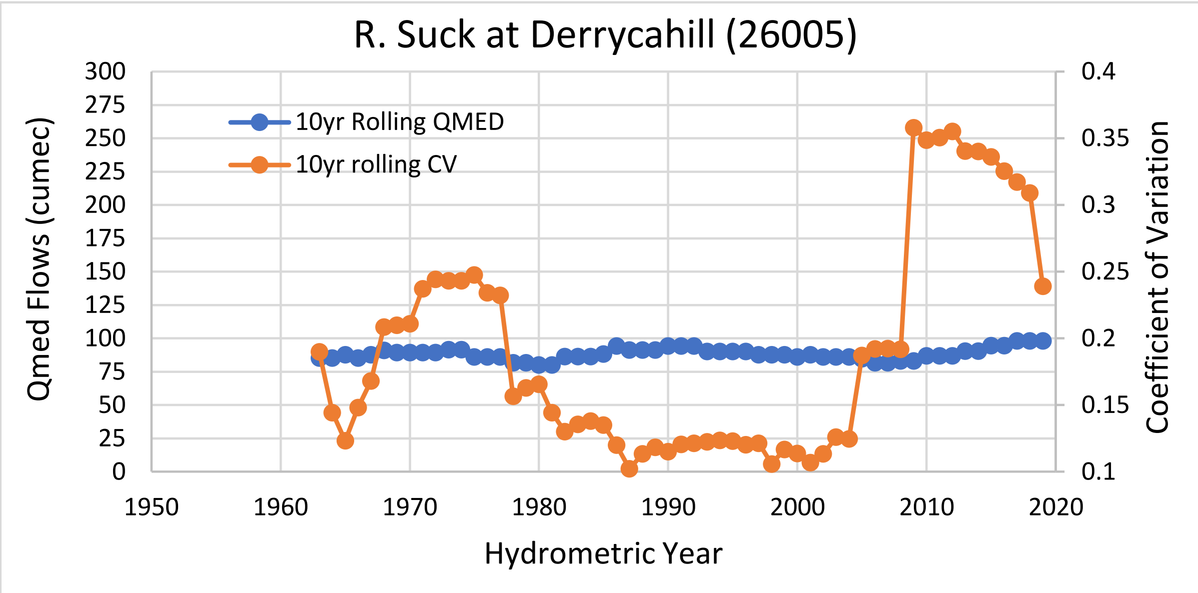

Figure 7-8 **10year rolling median flood and coefficient of variation for Derrycahill (26005)**

7.2.5 River Suck AM Flows at Rockwood

The River Suck Rockwood gauge provides 68years of AM series from 1952 to date which is reasonably long to examine potential trends in flood magnitudes. The median flood for the entire AM series is 56.4cumec and the coefficient of variation is 0.203 which is reasonably similar to both Bellagill and Derrycahill. The catchment area to the Rockwood Gauge is 642km^2, which is 53% of the catchment area to the downstream Bellagill gauge.

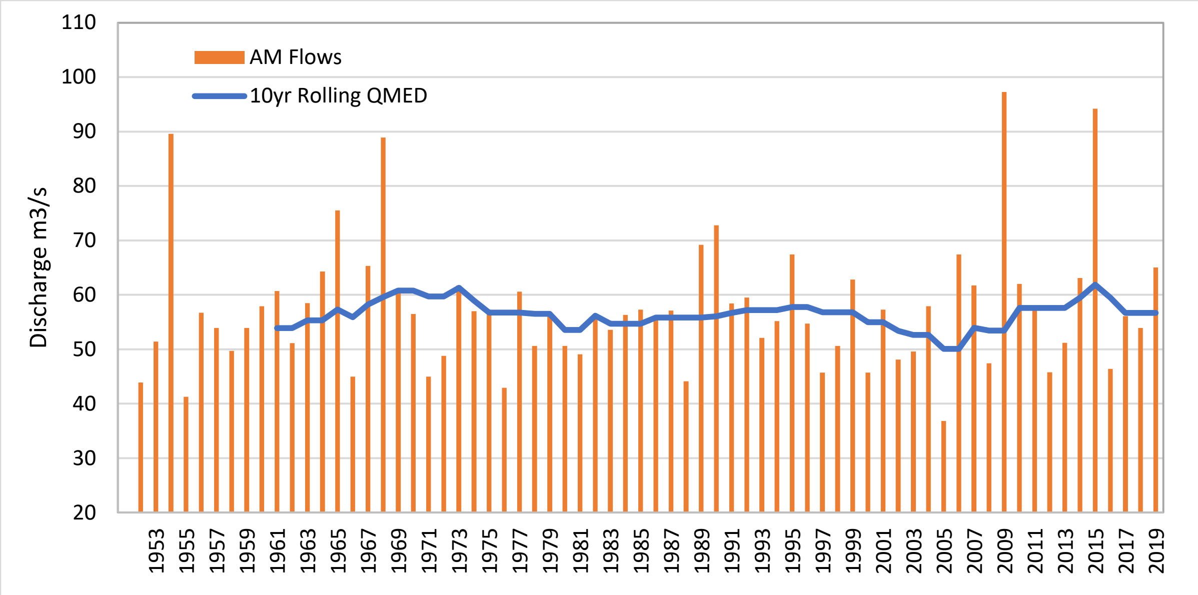

Figure 7-9 **Annual Maximum flood flow series for the River Suck at Rockwood with rolling 10year QMED estimate superimposed**

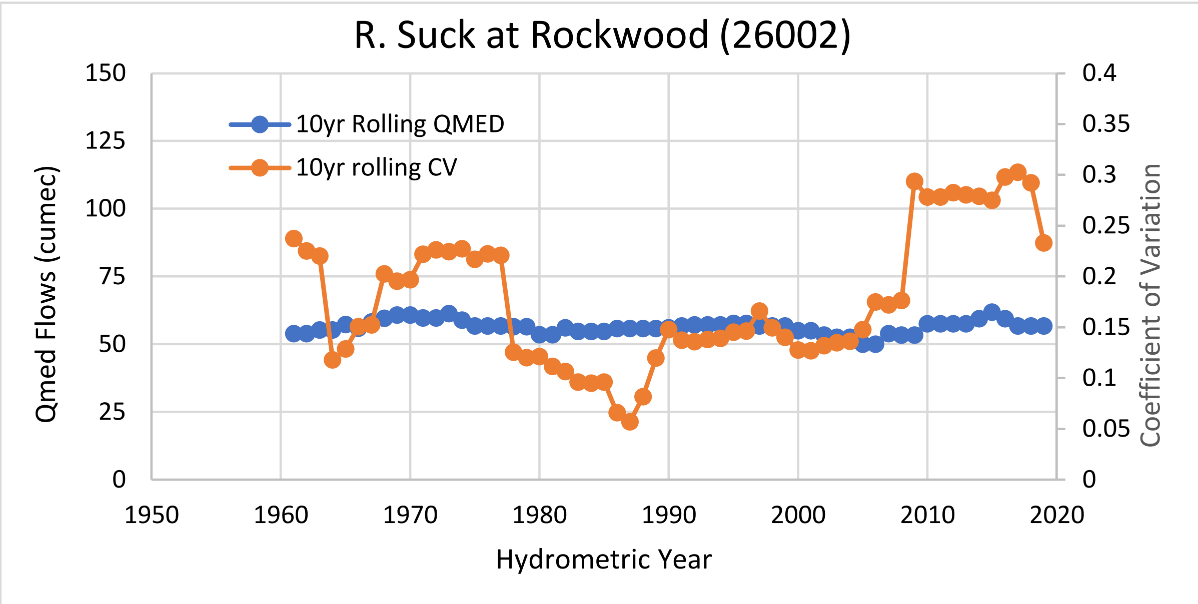

Figure 7-10 **10year rolling median flood and coefficient of variation for Rockwood (26002)**

Similar to the other downstream Suck and Banagher gauges, the AM series shows a wetter 50's and 60's, drier 70's and 80's and increasingly wetter 90's, 00's and 10's. Taking the entire record, the trend of increasing QMED based on a rolling 10year value is not very apparent. The coefficient of variation is considerably higher for the wetter decades and has significantly increased since 2000, which might suggest changes in the flood growth curve but is strongly influenced by a number and magnitude of very large winter floods which increases the variance. The QMED for the most recent two decades is 56.7cumec and the CV is 0.254. This increase in QMED is only 1.1% of the entire sample QMED which is not statistically significant. The QMED has only increased 0.05% which is not significant, however the change in the coefficient of variation is significant, suggesting increased variability.

7.2.6 River Suck AM Flows at Willsbrook

The River Suck Willsbrook gauge which is the most upstream and northerly of the gauges provides 68years of AM series from 1952 to date. The median Flood for the entire AM series is 24.0cumec and the coefficient of variation is much higher than the downstream gauges at 0.397. The Catchment area to the Willsbrook is only 185 km^2, which is 15.3% of the catchment area to the Bellagill gauge near Ballinasloe.

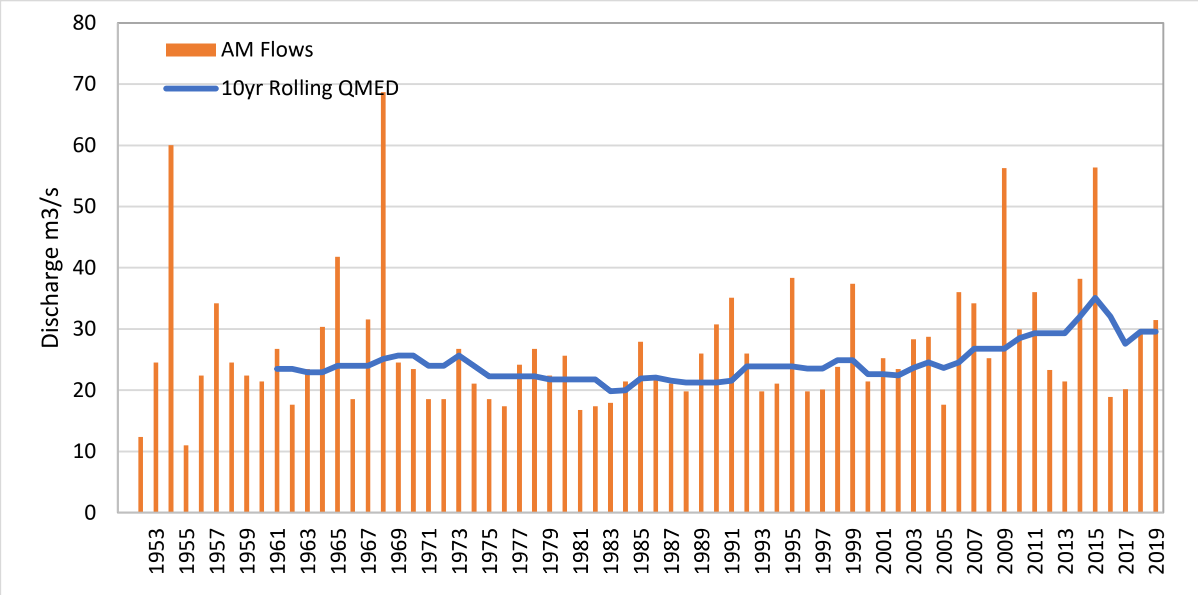

Figure 7-11 Annual Maximum flood flow series for the River Suck at Willsbrook with rolling 10year QMED estimate superimposed

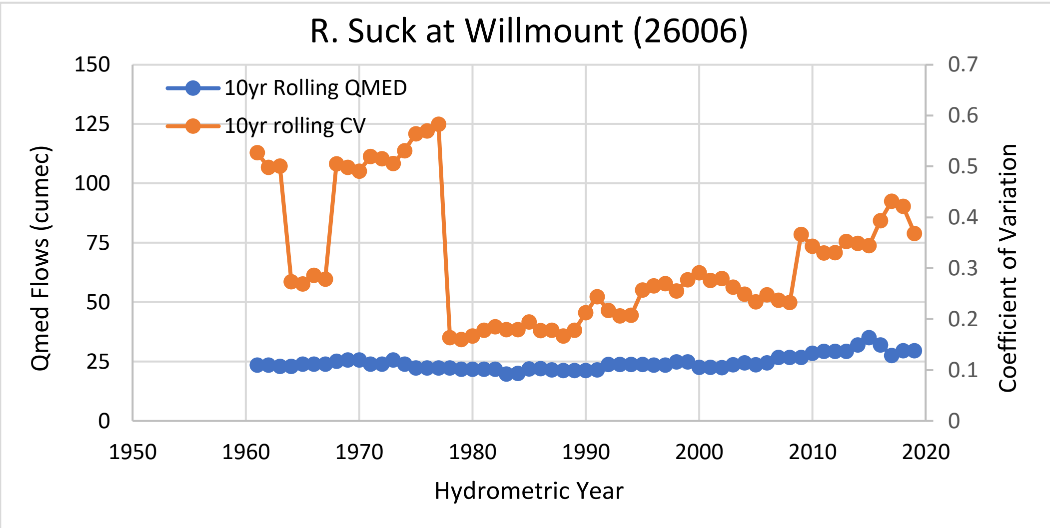

Figure 7-12 10year rolling median flood and coefficient of variation for Willsbrook (26006)

Similar to the other downstream Suck and Banagher gauges the AM series shows a wetter 50's and 60's, drier 70's and 80's and increasingly wetter 90's, 00's and 10's. Taking the entire record, the trend of increasing QMED based on a rolling 10year value is apparent. The coefficient of variation is considerably higher for the 50's and 60's and reduces dramatically in the 70's and 80's associated with no significant flows after which it increases for the 1990's onward. The QMED for the most recent two decades is 28.51cumec and the CV is 0.358. The QMED has increased 18.8% which is significant. The coefficient of variation has slightly decreased for the past 20years compared to the full record.

7.3 Additional Non -parametric EDA Examination

A standardised flood index $X_T = Q_T/QMED$ was performed on all AM series and a trend line fitted refer to Figure 7-13 below. This showed an increasingly positive trend between 1950 to date with an average annual increase for the six gauges of 0.33%. This trend fit can be very biased to the starting and finishing periods and may not reflect the overall trend or lack of trend. Not withstanding this, the last three decades display a more significant annual increase of 0.76% (average rate from the six gauges).

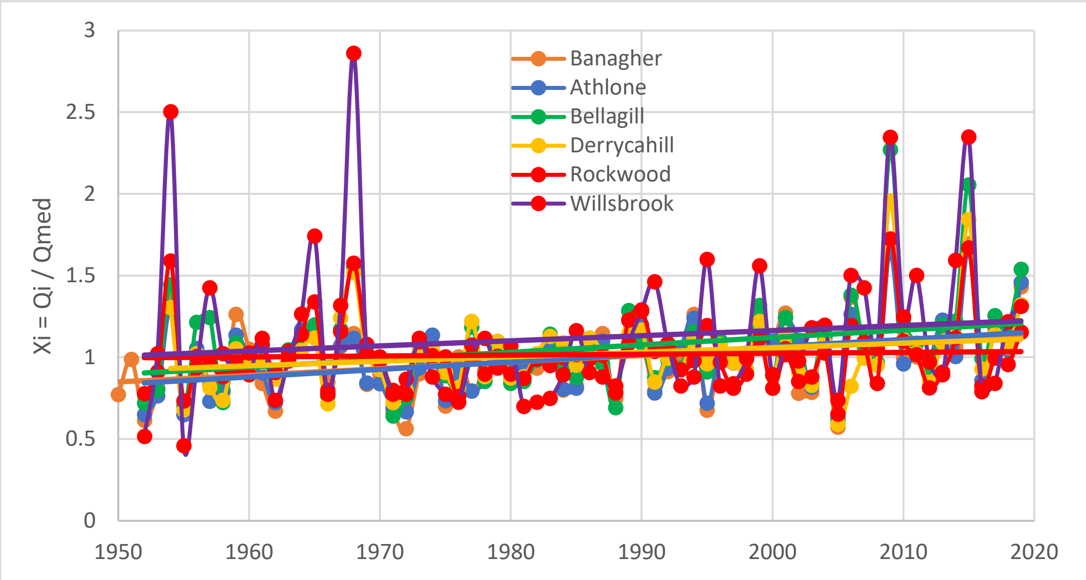

Figure 7-13 Trend in standardized AM Flood magnitudes at selected gauges (Xi = Qi/QMED, where i is the year index)

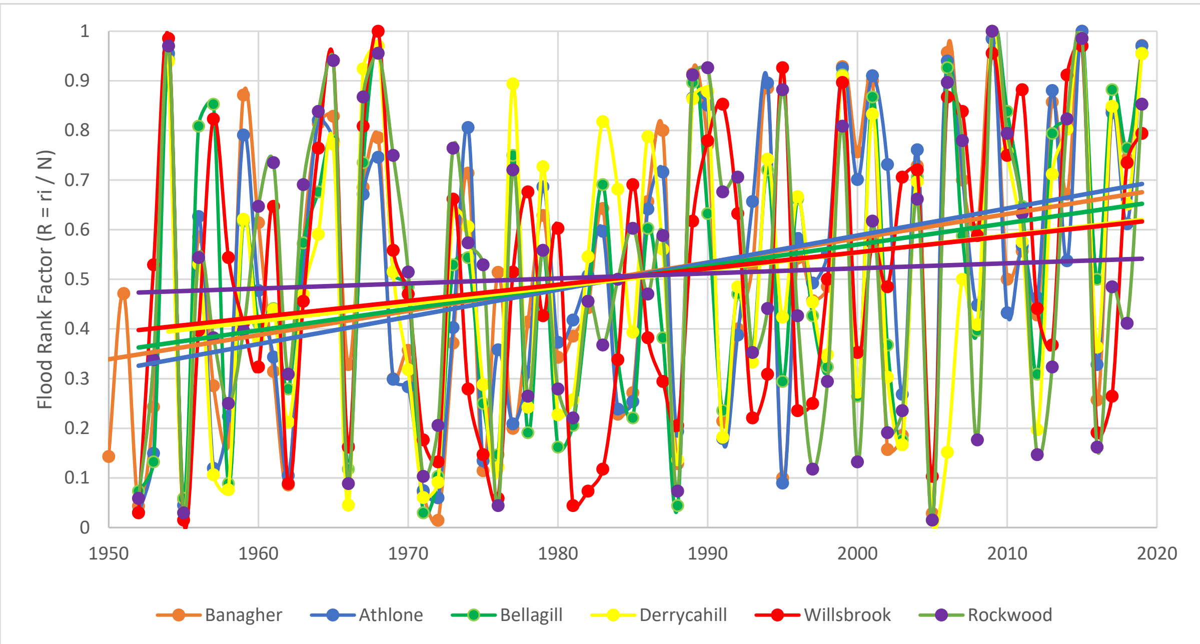

Figure 7-14 Trend in the Flood Rank (Ri = ri / N) at gauged sites (non-parametric test based flood ranking as opposed to magnitude)

The second analysis involves presenting the flood rank r_i of the AM series as a time series plot with the rank standardised by dividing by the sample number of the AM series ($R_i = r_i/n$).

Figure 7-14-presents this plot which shows an increased trend of higher flood ranks with time at all gauges suggesting increased floodiness.

7.4 Statistical test methods used in Trend Analysis

The following five statistical tests were used in detecting trends, shift and serial dependency in the AM flood flow series of the selected stations as set out in the OPW FSU WP-2.2 Appendix 1 (OPW, 2009).

- Tests for Serial persistence or trend
  - i) Mann-Kendall (non-parametric test for trend)
  - ii) Spearman's Rho (non-parametric test for trend)
- Tests for progressive change in the mean and median with time
  - iii) Mean-weighted Linear Regression test (parametric test for trend)
- Tests for a serial dependency of time series
  - iv) Turning Points (Kendall non-parametric test for randomness)
  - v) Rank Difference (Meachem non-parametric test for randomness)

These analyses were applied to the six gauges (2 Shannon and 4 Suck Gauges) and the results are presented here in Table 7-1.

Table 7-1 Trend Analysis Results of Full Annual maximum flow Series

Gauge Station	Record length	Manm-Kendall		Spearman's Rho		Mann Whitney		Turning Point		Rank difference	
		p-value	Result	p-value	Result	p-value	Result	p-value	Result	p-value	Result
Banagher	70	0.013	**S(5%)**	0.015	**S(5%)**	0.007	**S(1%)**	0.44	NS	0.846	NS
Athlone	67	0.001	**S(1%)**	0.002	**S(1%)**	0.008	**S(1%)**	0.844	NS	0.825	NS
Bellagill	68	0.015	**S(5%)**	0.017	**S(5%)**	0.014	**S(5%)**	0.999	NS	0.638	NS
Derrycahill	66	0.073	**S(10%)**	0.078	**S(10%)**	0.134	NS	0.921	NS	0.736	NS
Rockwood	68	0.615	NS	0.613	NS	0.365	NS	0.56	NS	0.938	NS
Willsbrook	68	0.066	**S(10%)**	0.077	**S(10%)**	0.015	**S(5%)**	0.02	**S(5%)**	0.288	NS

The tests for trend in the AM flow series returned definite significance at 5 and 1-percentiles of positive (increasing) trend in flood magnitudes for both River Shannon gauges and for the Bellagill gauge at Ballinasloe. The upstream gauges show some significance at the 10-percentile for a trend of increased flooding at Derrycahill and Willsbrook but no trend of significance detected at the Rockwood gauge. In respect to serial dependency of the AM series, no significance was generally detected at all of the gauges except for one positive test 2% significance at Willsbrook generally suggesting that the AM series is random.

7.5 Trend Analysis Conclusions

The trend analysis shows definitely that the QMED for a number of the gauges considered has increased significantly with time and also the frewuency of flooding and particularly this has occurred from the 1990's onwards at the Shannon gauges of Athlone and Banagher and at the Suck gauges of Bellagill, Derrycahill and Willsbrook. Such a trend is most likely to be primarily associated with increased rainfall amounts as opposed to catchment land-use changes.

Table 7-2 QMED from full record and recent 30years

Gauge Station	Full Record length (years)	QMED Full Record	QMED Recent 30years
Banagher	70	436.2	463.6
Athlone	67	242.0	254.6
Bellagill	68	93.6	101.8
Derrycahill	66	89.5	91.9
Rockwood	68	56.4	57.3
Willsbrook	68	24.0	26.0

Trend examined in the coefficient of variation, which effects the flood growth curve was not definite for any of the gauges based on 10 year rolling averages.

Consistent with the precautionary approach and the increasing trend in QMED, the QMED estimates at the gauged sites should be based on the period from 1989 onwards (the recent 3 decades), but the growth curve should be based on available full record length given the absence of a definite trend and requirement for a long record. Therefore the design growth curve for the Suck is that set out in Table 5-18 and the QMED estimate for the Pivotal Site at Bellagill is 101.8cumec with a statistical standard error based on the 31years of 6.47%.

8 Future Change Allowances

8.1 Introduction

The range of potential impacts from climate change varies and such projected impacts have significant uncertainties associated with global climate predictions and local hydrological variation for periods more than 20 years into the future. The current OPW guidance for flood relief schemes and for catchment flood risk management is to include and assess two scenarios to quantify the sensitivity of flood risk to potential climate change, namely, the Mid-Range Future Scenario (MRFS) and the High-End Future Scenario (HEFS) and the current recommended allowances are detailed in Table 8-1.

Table 8-1 Allowances for Future Change Scenarios

	MRFS	HEFS
Extreme Rainfall Depths	+20%	+30%
Flood Flows	+20%	+30%
Urbanisation	Locally variable and dependent on catchment	Locally variable and dependent on catchment
Forestation	-1/6Tp (hours)	-1/3Tp (hours)+10%SPR

Forestation is considered to potentially reduce the time of peak of a rainfall event and to increase the standard percentage runoff (SPR).

8.2 Potential Climate Changes

There is a high degree of uncertainty in relation to the potential effects of climate change and particularly in respect to fluvial flooding, and therefore a precautionary approach is required. Examples of precautionary approach for future planning of urbanised areas include:

- Recognising that significant changes in the flood levels and flood extent may result from an increase in rainfall and accordingly adopting a cautious approach to zoning lands in these potential transitional areas.
- Ensuring that the finish levels of structures are sufficient to cope with the effects of climate change over the life time of the development.
- Ensuring that structures to protect against flooding (e.g. defence walls / embankments) are capable of adaptation to the effects of climate change when there is more certainty about the effects (e.g. foundations of flood defence designed to allow the future raising of flood wall to combat climate change).

The ICPP Global climate models (Echam 5 (EC5), Hadley Centre High Sensitivity (HAH) and Hadley Centre Low Sensitivity (HAL) and their downscaled simulations for Ireland show significant projected decreases in mean annual, spring and summer precipitation amounts by mid-century. The projected decreases are largest for summer, with reductions ranging from 0% to 13% and from 3% to 20% for the medium-to-low and high emission scenarios, respectively.

The frequencies of heavy precipitation events show notable increases of approximately 20% during the winter and autumn months.

The impact of climate change on fluvial flows is uncertain but given that flooding in the River Suck is a winter rainfall system then projections of 20% increase in precipitation is likely to result in a corresponding effect on catchment flooding.

In light of much uncertainty in respect to climate change effects on catchment hydrology, it is considered prudent to retain the present OPW recommendations for flood relief schemes of a potential 20% increase in flood flows at the mid-range future Scenario and 30% increase in flood flows at the High-End Future Scenario.

Trend analysis presented earlier in Section 7 identified a significant increasing trend in the magnitude of a flood with time for the River Suck and Shannon gauges and projected an average increase in the QMED flow of 0.76% per annum. At this rate, the QMED will over the next 50 years could increase by c. 38% which exceeds the current recommended HEFS of 30%. It was not possible to predict how the flood growth curve might change over time. It is suspected that potential increase variability in meteorological conditions due to increased energy from increased global temperatures may also change the growth curve behaviour and could steepen.

8.3 Potential Land-use changes

The River Suck catchment is a relatively large catchment at 1599km^2 to the River Shannon. The Suck catchment is predominantly a rural catchment and is dedicated to agricultural pasture use predominantly associated with sheep and cattle rearing. The land-use within the Suck catchment based on the FSU PCDs is 70.2 % pasture, 16.2% peatlands, 8.0% forestry, 2.5% alluvial along the river channels and 0.49% urban (Corine landcover 2018).

There are many uncertainties surrounding the future of agriculture within the catchment and is primarily dictated by economics. The degree of intensification into the future will be strongly impacted and limited by environmental factors and greenhouse emissions, and by the EU Common Agricultural Policy and changing world markets, potentially making agriculture and pastoral activity less economically viable. Such pressures may change the farming activity and this into the future may also be affected by a change in typical annual temperatures with climate change resulting in potential changes in crop types grown. Given the relatively low forestry fraction within the catchment, it is unlikely that deforestation will be a driver.

Peat Bog areas which represents 16.2% of the landcover based on the Corine classification has apparently reduced since 1990 by 14.8% and since 2000 by 13.1%. The Corine land cover classification indicates that no reduction has occurred since 2006. The classification of peat bogs appears to for the different periods appear not to be very consistent and care in evaluation the figure needs to be applied. In any case, the reduction in peat bogs within the catchment has reduced through more recently protection afforded under the habitats directive and the ban on commercial peat harvesting and therefore drainage of such peatlands to create more agricultural land or forestry within the catchment is unlikely to be a significant factor into the future.

The main pressure on peatlands may come potentially from forestry and renewable projects. The growth of forestry within the catchment is projected to grow over the next 20years by up to 20% by 2035 in line with the Forest Service Strategy (2006). Given that forestry (woodland and commercial) only represent 8.2% of the catchment area and therefore such projected change in forestry coverage would have a negligible impact on river flows in the lower catchment through Ballinasloe. The effect of afforestation can be to initially increase runoff rates through the introduction of new drainage paths, but as the forest matures, improved infiltration into the root zone occurs and a reduction in the annual runoff rate can be achieved. Under prolonged rainfall conditions which are the critical conditions for flooding at Ballinasloe, the effect of forestry on flood runoff is not significant with the ground saturated and percentage runoff dictated by the land gradient and soil and geological characteristics.

It is concluded that changes in land use as a result of projected forestry growth within the suck catchment will not result in any significant changes to flooding through Ballinasloe.

Table 8-2 Corine land cover areas (km^2) within the River Suck Catchment

Year	Broad leaved Forest	Coniferous Forest	Mixed forest	Trans Woodland-shrub	Total	percentage
1990		40.44	2	77.59	120.03	7.51%
2000		8.07	1.98	103.67	113.72	7.11%
2006		52.07	10.72	78.18	140.97	8.82%
2012	5.81	75.5	12.92	34.24	128.47	8.03%
2018	6.32	68.8	13.14	39.86	128.12	8.01%

Table 8-3 Corine land cover agriculture areas (km^2) within the River Suck Catchment

Year	pastures	arable land	cultivation	natural grasslands	Total	percentage
1990	1065.68	12	35.07	37.71	1150.46	71.95%
2000	1028.78	40.82	30.96	40.93	1141.49	71.39%
2006	1095.46	3.51	0.33	98.13	1197.43	74.89%
2012	1123.35	4.83	0.92	65.9	1195	74.73%
2018	1121.65	4.77	0.85	65.84	1193.11	74.62%

Table 8-4 Corine Land Cover peat and wet areas (km^2) within the River Suck Catchment

Year	Peat Bogs	marshes	Water bodies	Watercourses	Total	percentage
1990	304.11	8.82	4.19	2.83	319.95	20.01%
2000	293.29	7.13	1.98	2.78	305.18	19.09%
2006	241.84	6.12	1.43	0.015	249.405	15.60%
2012	257.57	6.21	1.41	0.013	265.203	16.59%
2018	259.2	6.21	1.4	0.013	266.823	16.69%

8.4 Urban Development

The Suck Catchment and its main tributaries are all rural catchments with very low urban fractions. The Corine Land cover mapping shows an urban fraction of the Suck to be only 0.49%. The Corine mapping indicates the principal change in urban fraction between 1990 and 2006 with no significant increase between 2006 and 2018. The Corine mapping from survey year to survey year for urban cover is not very consistent, showing some urban areas in contradiction to mapped extents from other survey years.

Table 8-5 Corine Land Cover discontinuous Urban areas within the River Suck Catchment

Survey Year	Urban Area km^2	Urban fraction percentage
1990	6.44	0. 40%
2000	8.07	0. 50%
2006	8.62	0.54%
2012	7.91	0. 49%
2018	7.92	0.49%

Increased future urban development as a result of the increased population is likely to impact flooding in the following ways:

- Increase the surface runoff from the catchment by increasing impermeable areas that were previously greenfield sites (i.e. rural runoff rates).
- Increase the proportion of surface runoff draining to urban drainage networks which have a direct surface outfall to a watercourse. This increases the quantity and the response time for rainfall to enter the watercourse.

The planning policy within Galway County Council as clearly set out in the current County Development Plan is to minimise the impact of urbanisation on flooding through the implementation of SUDs policy that requires the peak storm rate for new developed urban areas not to exceed its pre-development greenfield annual maximum flow. The Flood Risk Management Planning Guidelines (2009) projects critical flood plain areas from development and potential infill and encroachment.

Ballinasloe and Tuam are designated as key towns in the forthcoming Development Plan (for the period 2022 to 2027), with both Tuam and Ballinasloe targeted for a 30% increase in population to 2031. This would increase Ballinasloe's 2016 population from 6,662 to circa 8,600 people and Tuam's 2016 population from 8,767 to circa 11,300 people (1.72% per annum increase). A projected population increase for Ballinasloe of 1938 at 3.22persons per residential unit would require 600 residential units and at 0.07ha which includes 50% over-zoning, would require 42.6ha of urban development in Ballinasloe.

The issue paper also notes that within the development period 2011 to 2016, 76.6% of all new residential development was associated with one-off housing. Other towns within the suck catchment are not targeted as major growth areas.

In any case, the impact of future urbanisation on flooding in the River Suck will not result in a significant increase in the flood flows within the Suck River through Ballinasloe. A potential future doubling of the urban fraction from 0.49% to 1% will only result in an increase in the flood magnitude in the Suck of 0.75% based on FSU Urbanisation Factor adjustment for QMED which in the context of climate change is a very minor potential increase.

In conclusion, the very limited extent of the urban fraction within the catchment and the future likely increase to this fraction and the SUDs policy concerning urban development will result in insignificant impact on the River Suck Flows through Ballinasloe. Potential changes at the local urban drainage scale at Ballinasloe will need to be taken into account in the protection and design of defended lands as part of the hydraulic modelling and countermeasure options. Increased urbanisation of these lands will in the absence of engineered attenuation will increase the time of peak and peak runoff magnitude and potentially the volume of runoff through reduction in pervious areas.

On the scale of the Suck catchment and its larger tributaries to Ballinasloe the projected change in urban fraction is very minor in respect to impact on flood flow and flood level magnitudes in the river. However for the local sub-drainage areas within Ballinasloe that are or potentially may be located behind flood defences the potential increase in urban fraction will increase the volume of flood water to be potentially stored and pumped in order to avoid localised flooding associated with flood defended options. The future planned urbanisation within Ballinasloe and associated increased impervious areas should be included for in the hydraulic modelling of any proposed defended option.

8.5 Recommended Future Change Allowances

It is recommended that the climate change allowances of 20% and 30% increase at the Mid-Range Future Scenario (MRFS) and the High-End Future Scenario (HEFS) be included for both in respect to storm rainfall and flood runoff in assessing the adaptation of the proposed flood relief scheme to future change. Given the significant increasing trend identified in the Suck and Shannon AM series from the 1990’s onwards, it may also be prudent to include a higher allowance of up to 40% to assess the sensitivity of flood relief scheme to extreme effects of climate change.

Future potential catchment land-use changes, agriculture and forestry are not considered in the case of the Large River Suck catchment and its tributaries the Deerpark and Bunowen as significant drivers for the change in the design flood magnitudes and hydrograph shape through Ballinasloe. The potential impact of local urbanisation within or contributing to flows within potential defended lands will require careful consideration, particularly where temporary storage or pumping of storm flows from the defended areas might be required.

9 Design Hydrograph determination

9.1 Introduction

A variety of methods have been assessed including using actual hydrograph shapes for the River Suck at Bellagill from previous flood events in particular the November 2009 flood hydrograph and upscaling and downscaling this hydrograph based on the peak flow. Other events were also assessed including the December 2015 recorded flood hydrograph.

9.2 Recorded Flood Hydrographs

9.2.1 November 2009

The recorded Flood Hydrograph for the River Suck at Bellagill is presented below in Figure 9-1. This represents the hydrograph for the maximum historical flood which saw significant rainfall from the 20th October to 17th November followed by a number of days of more intense rainfall. This is evident below with flood flows continually rising to the 18th of November and then steeply rising to a flood peak on the 21st of November.

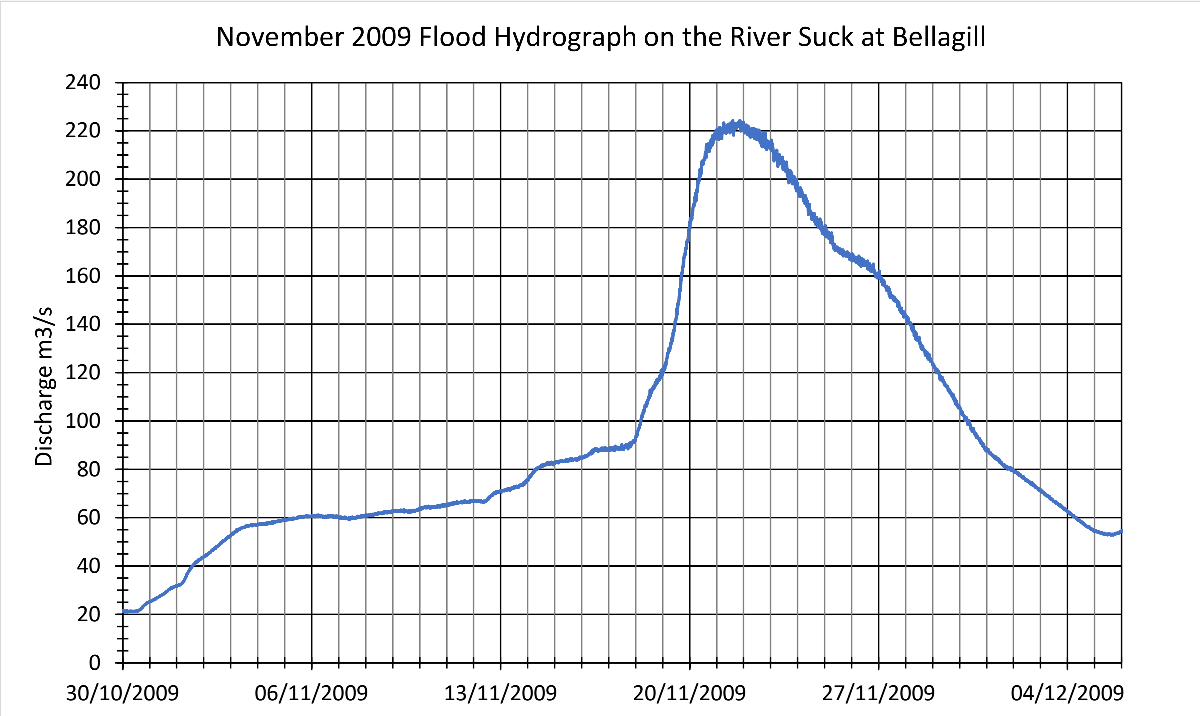

Figure 9-1 Recorded Flood Hydrograph for River Suck 30 Oct 2009 to 6 December 2009

9.2.2 December 2015

The December 2015 peak flow at Ballinasloe represents the second largest flood event at the gauge and has a single definite peak that occurred on the 7/8th December. This hydrograph in the rising and falling limbs around the peak is very similar in shape to the November 2009 event.

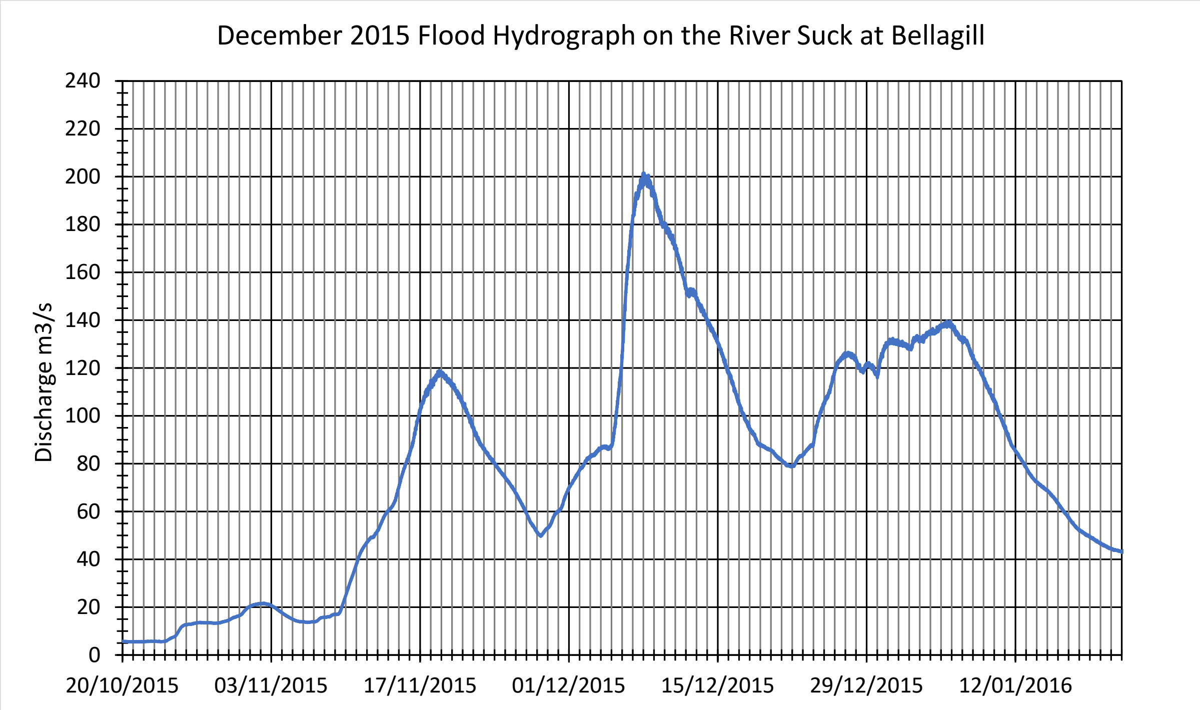

Figure 9-2 Recorded Flood Hydrograph for River Suck 30 Oct 2009 to 6 December 2009

9.3 FSU Hydrograph Width Analysis

The FSU hydrograph width method as outlined in the FSU Technical Research Report Volume III was applied. Importantly, the Bellagill station is listed as one of the FSU pivotal sites for the hydrograph method. Fortunately, the 2009 event at Bellagill was included in the FSU hydrograph width method, being one of the latter packages to be completed for the FSU.

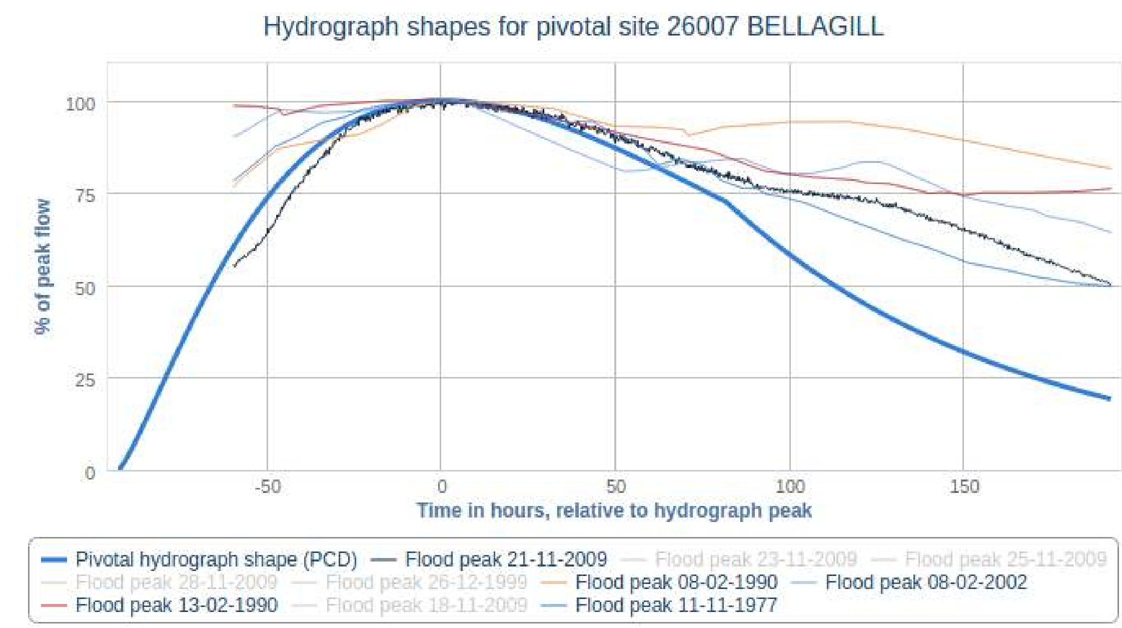

Figure 9-3 FSU Hydrograph Width Method for River Suck at Bellagill

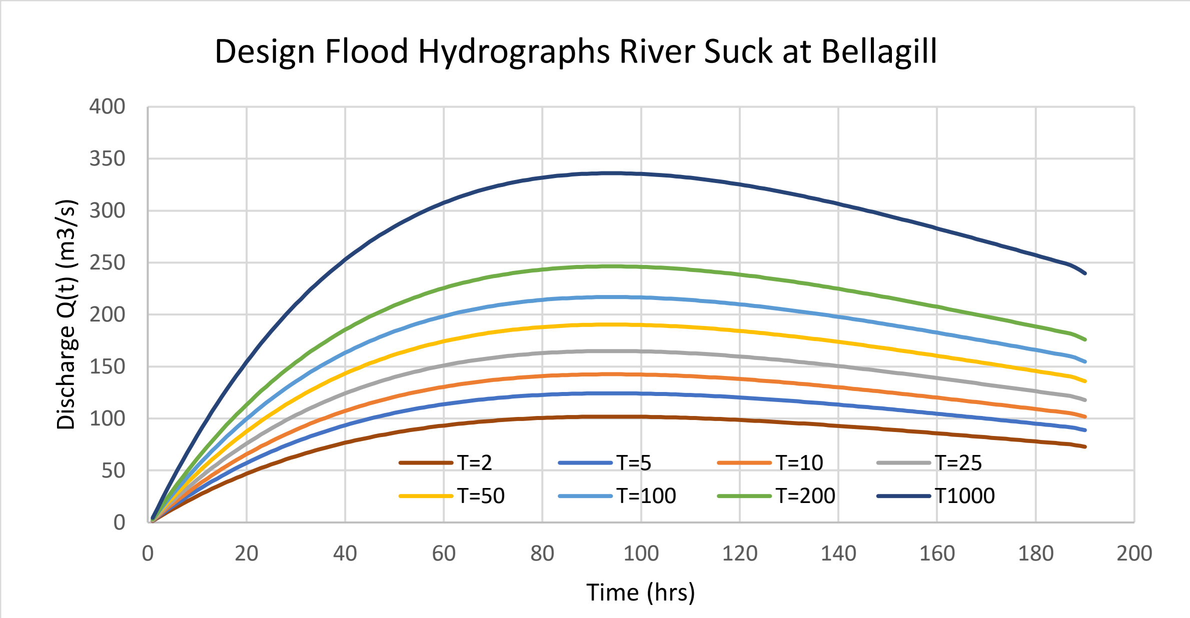

Figure 9-4 **Computed Design Return Period Hydrographs at Bellagill from the FSU hydrograph width method**

9.4 Fitted hydrograph shape Method

This method uses the actual recorded shape of the November 2009 and the December 2015 subject to standardization by dividing all flow ordinates by the event Peak flow magnitude. It was found that these hydrographs reasonably agreed with each other for the flow portion above the standardized flow of 0.5 (50% of the peak flow). The average hydrograph shape was extracted from the two events as presented in Figure 9-5 and Figure 9-6. This hydrograph can then be scaled up by multiplying it by the estimated return period flood peak at each of the HEPS. Refer to Figure 9-7 for Bellagill.

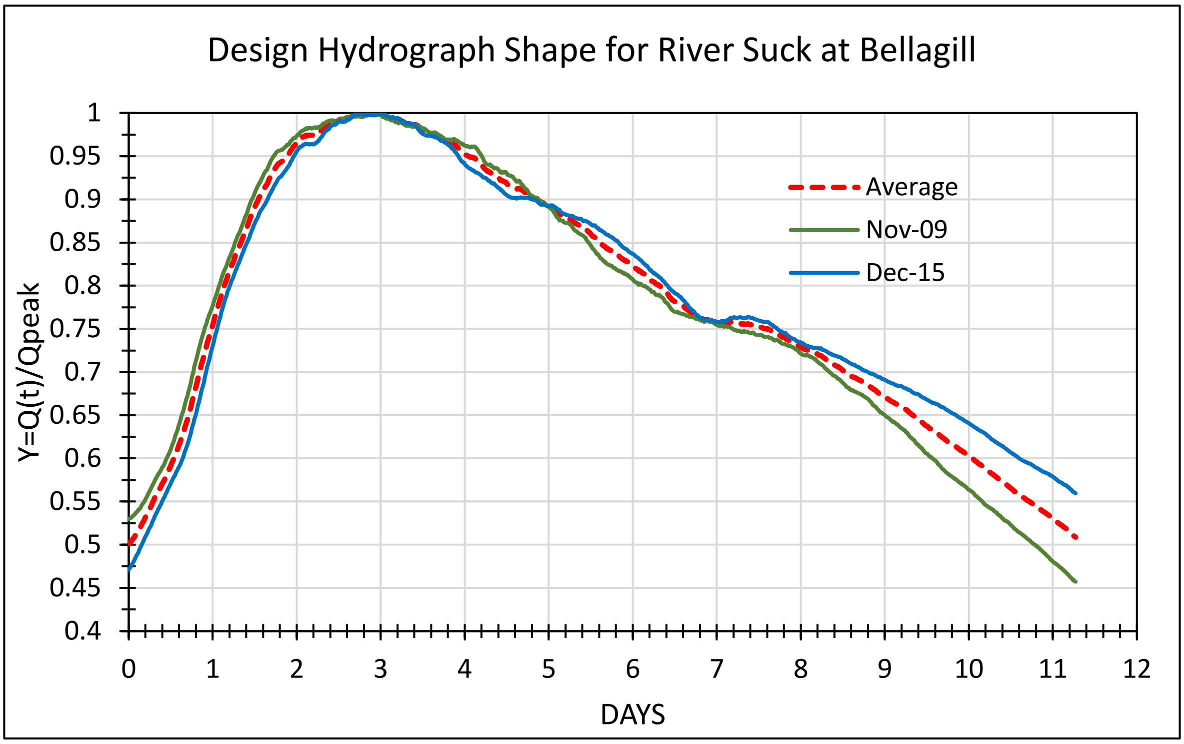

Figure 9-5 **Fitting Hydrograph Shape to recorded Flood events of Nov 2009 and Dec 2015**

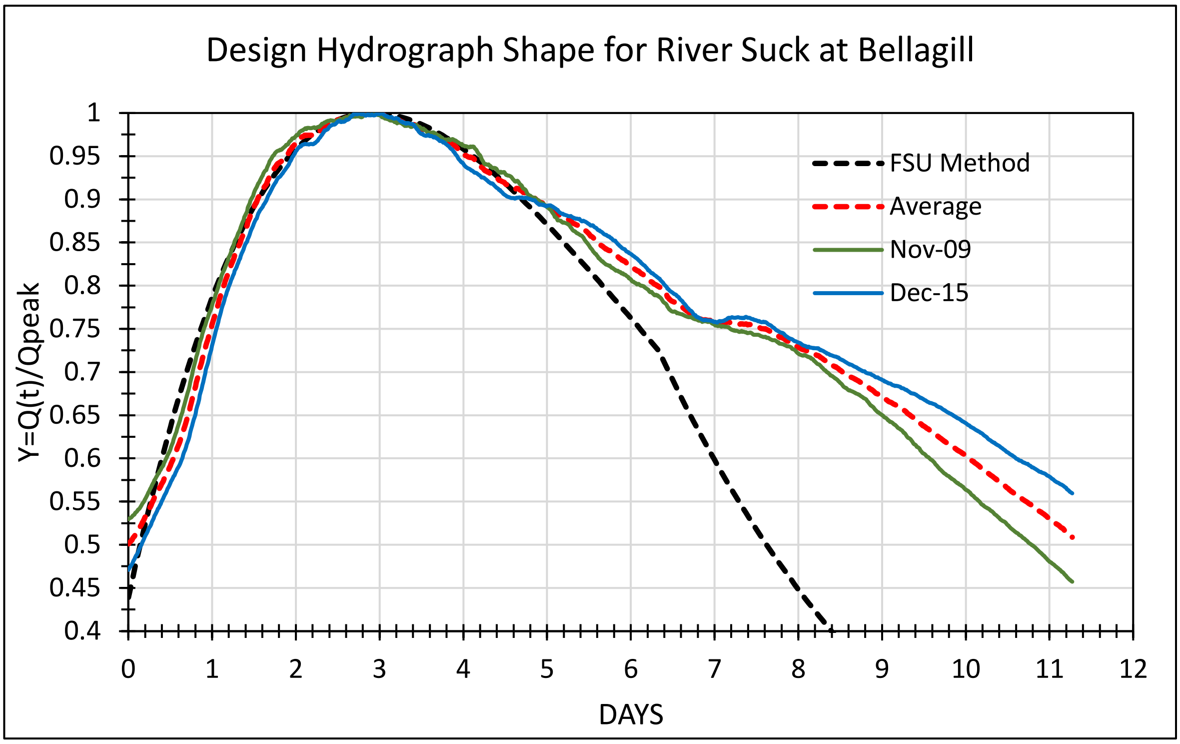

Figure 9-6 Comparison between FSU hydrograph method and the fitted Hydrograph method

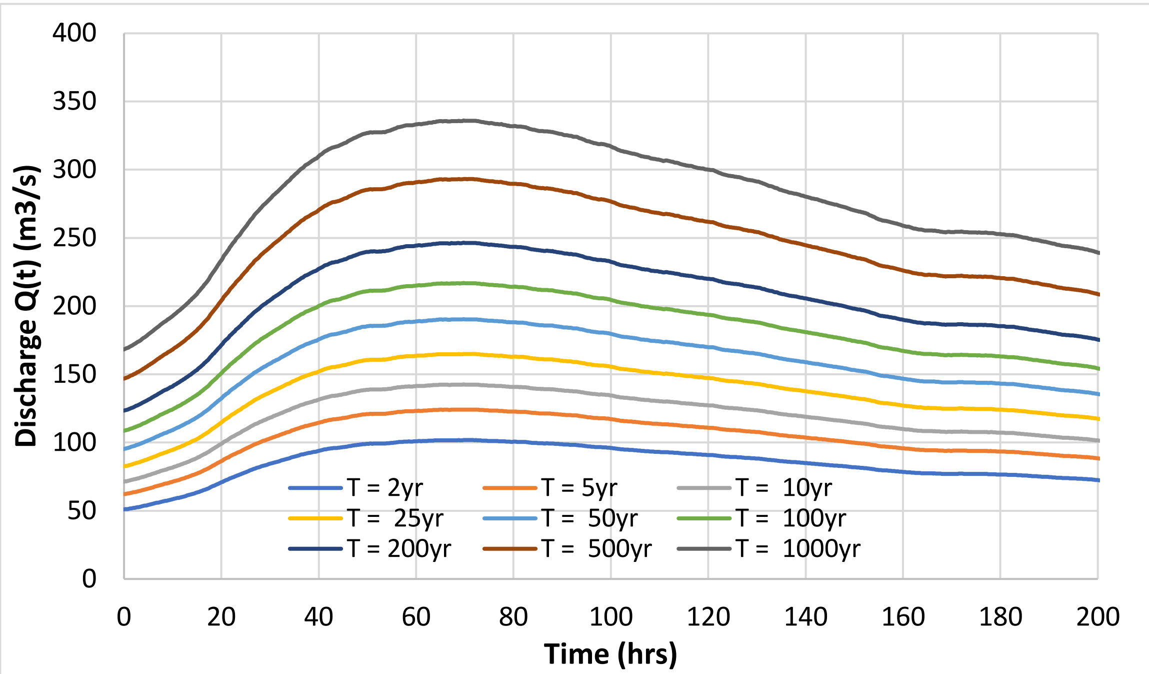

Figure 9-7 Design Flood Hydrographs for River Suck at Bellagill from the fitted hydrograph method

9.5 Design Storm and Triangular Unit Hydrograph

The FSR Synthetic hydrograph method based on the time to peak Tp was applied to the River Suck using the FSR time to peak of 27hours and a Storm Duration of 55hours. The baseflow was estimated based on the FSR method at 38cumec and the percentage runoff for quick response runoff was calculated at 38% for an FSR WRAP soil class of type 2, a catchment wetness index CWI of 125mm and a total rainfall depth of 99.3mm in the 55hour storm duration. A winter rainfall profile for suck to Ballinasloe from the FSU web-portal was applied.

At the calculated percentage, quick runoff rate of 38% (the effective rainfall depth) was 37.7mm over the 1207km^2 catchment area. The rainfall profile and the computed hydrograph are presented below in Figure 9-8. This method which is based on the FSR methodology derived for UK catchments produces a hydrograph that peaks sharply and recedes sharply and does not generally produce great results for Irish catchments, particularly the larger more damped catchments such as the Shannon and the Suck. This method gives an estimated 100year peak flow of 316.6cumec, some 46% higher than the estimated peak flood flow at Bellagill of 216.9cumec from the flood frequency analysis presented earlier.

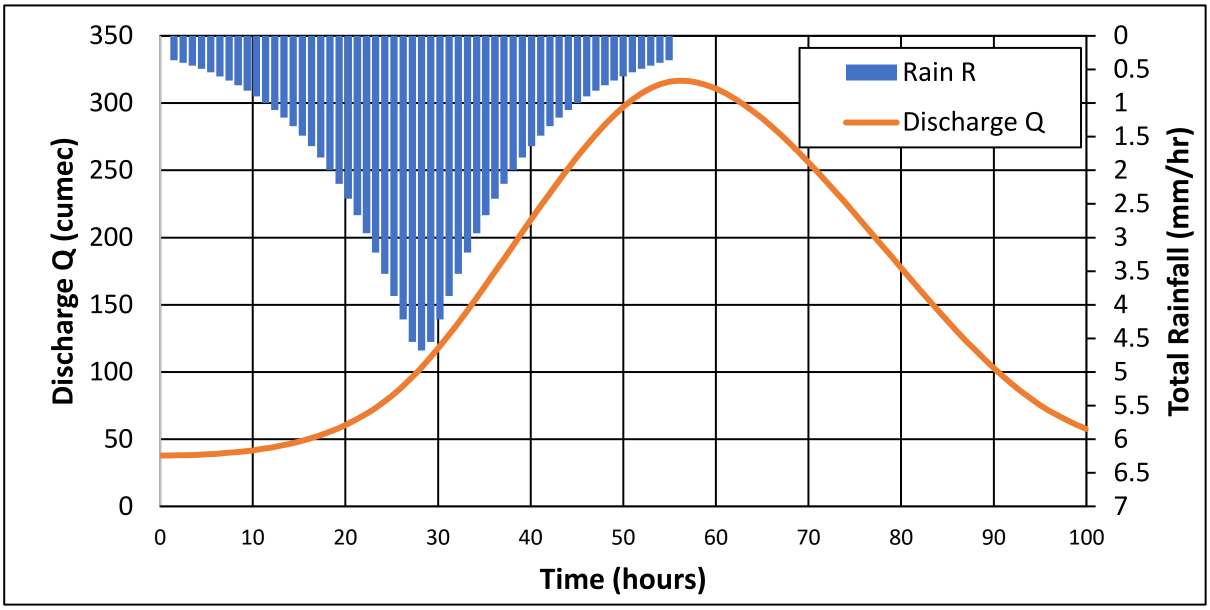

Figure 9-8 **100year Design Hydrograph at Bellagill using FSSR Triangular Unit hydrograph with Design Storm Method**

9.6 Modified Triangular Hydrograph Method for River Suck to Ballinasloe

Adjusting the flow ordinates of the unit hydrograph so that the peak matches the estimated peak of 216.9cumec will significantly reduce the flood volume which is not considered realistic for the Suck. Another option considered was to adjust the hydrograph shape such that it matches the flood peak of 216.9cumec by reducing the ordinates and expanding the base so as that the correct volume is preserved beneath the curve. This results in the unit hydrograph peak flow of Qp = 125/Tp cumec per 100km^2 for 1cm or effective rainfall. It should be noted that the original FSR(1975) triangular hydrograph has the peak ordinate defined as Qp = 220/Tp cumec per 100km^2 for 1cm of effective rainfall based on UK catchments.

The results of this simulation are presented in Figure 9-9 below. This approach achieved the peak flow of 216.9cumec and is slower to recede. However, this flood hydrograph shape when compared to the observed hydrograph for 2009 event which has a similar peak flow but exposes its lack of volume and duration of the higher peak flows.

The true shape of a flood hydrograph for the River Suck at Bellagill requires higher percentage runoff and the inclusion of intermediate and slow hydrograph responses. The duration of the peak and flood volume are significantly less which is not desirable given the attenuating role of the downstream floodplain at Ballinasloe.

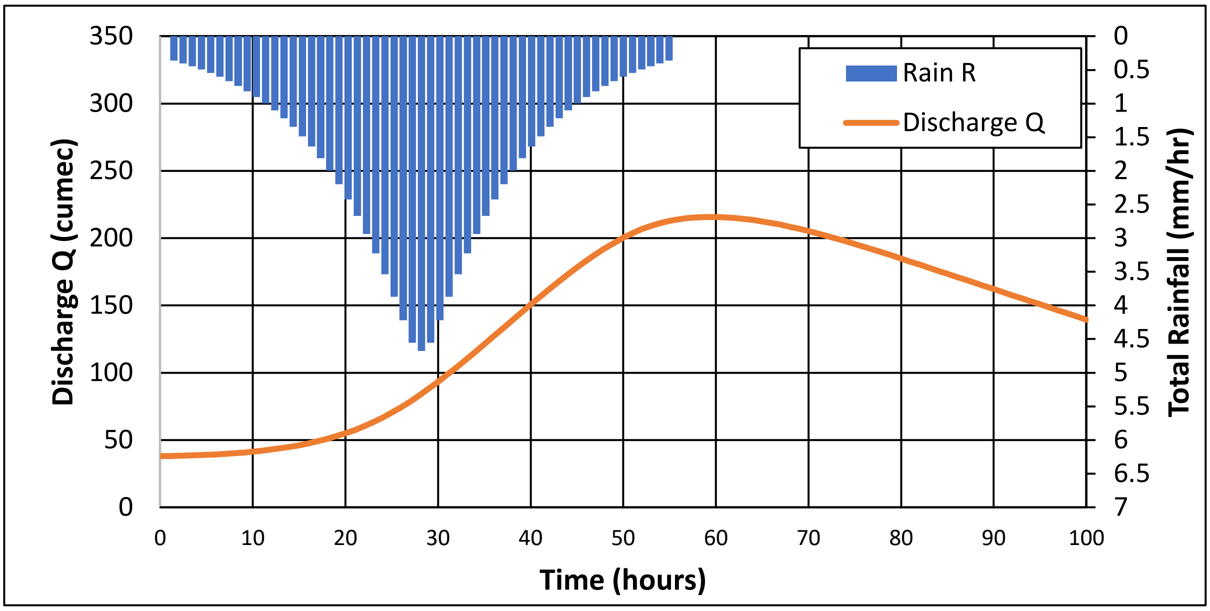

Figure 9-9 **100year Design Hydrograph at Bellagill for a modified FSSR Triangular Unit hydrograph (Qp =125/Tp).**

The November 2009 flood event hydrograph and rainfall presented in Chapter 3 was modelled using this modified triangular hydrograph and the results are presented below in Figure 9-10. To achieve similar peaks, a percentage runoff rate of 50% was specified. The results demonstrated that the response is approximately 11hours too early and the recession is earlier and sharper but considered a reasonable representation.

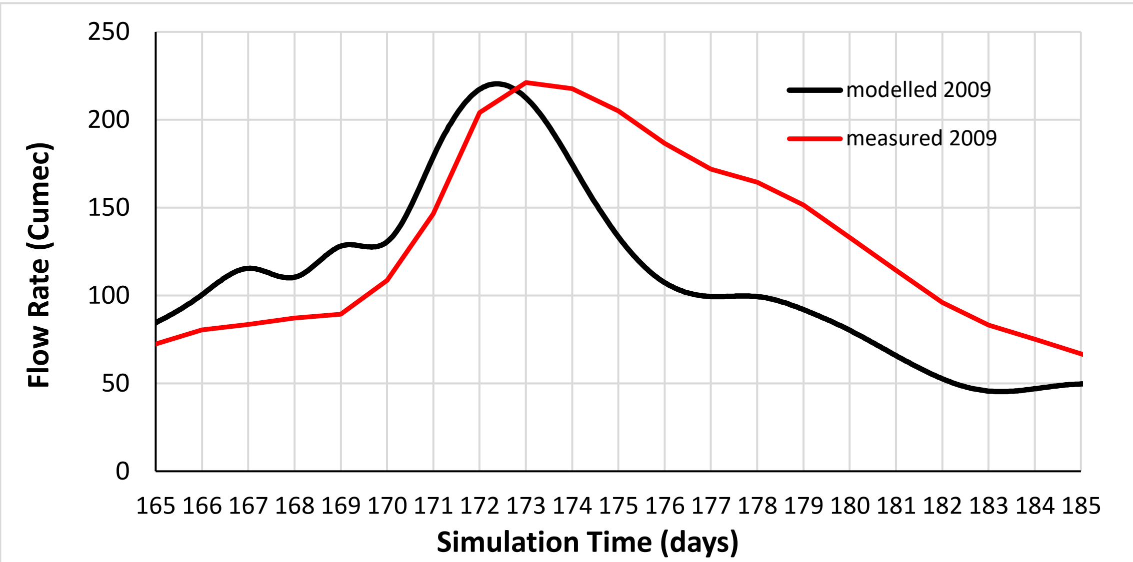

Figure 9-10 **Comparison between computed and observed hydrograph for the 2009 flood at Bellagill using the modified triangular unit hydrograph method.**

This modified FSR unit hydrograph and design storm method which adjusts the unit hydrograph shape to achieve the recommended design peak flows is used on all of the tributaries to generate a hydrograph shape for the different return period events.

9.7 Recommended flood Hydrographs

It is proposed to adopt two methods for defining the design of flood hydrographs for input to the Hydraulic flood model. The first method is to adopt the hydrograph shape for the Suck River as presented in section 9.4 and scale up to the design flow magnitude at the HEPS. The tributary inflow will be defined from the residual hydrograph (i.e. the difference between the upstream and downstream Suck hydrographs at the confluence) for each of the inflowing tributaries.

The second method will be to use the modified Triangular hydrograph method on all tributaries and on the River Suck as outlined in Section 9.6. This method was found to reasonably represent the rising limb and the peak of the 2009 flood, as shown in Figure 9-10. This second method will specifically be used to examine local flooding on the smaller ungauged tributaries also will allow examination of timing effects from these tributaries on the downstream Suck hydrograph. Additional fine tuning of these methods will be required during the hydraulic modelling.

10 Uncertainty in Flow prediction

10.1 Introduction

Design flow analyses are statistical assessments which originate from observed hydrological data. The uncertainty in the design flow predictions can be associated with

- The statistical error of the flood quantile derived from the hydrometric data – sampling error and the statistical standard error of the regression equation applied (i.e. FSU estimation equation)
- The error associated with the selected statistical distribution referred to as model error
- The error associated with the flood flow and water level measurement – error in the rating relationship referred to as measurement error referred to as rating error.
- The error associated with catchment data and changes from urbanization, afforestation, drainage morphological and vegetation effects on the river control resulting in a change in the hydrological response,
- The error associated with non-stationarity from climate change

The above is not an exhaustive list but presents the primary sources of error and uncertainty in the hydrological analysis.

10.2 Statistical Error

In Section 5, detailed analysis was carried out in to quantifying the statistical standard error of the flow Quantiles Q_T. The Bellagill gauge site is the selected pivotal site for the HEPs along the River mainline. The statistical error associated with the QMED estimate from Bellagill is estimated based on the standard error calculation for Extreme Value type distributions to be $se(QMED) \approx 0.36QMED/\sqrt{N}$ which for the Bellagill AM series with 68 years of data and a QMED of 93.6 cumec represents a percentage standard error of 4.36%. Based on the Trend Analysis presented in Section 7 only the recent decades from 1989 to date will be used to calculate the QMED giving a revised QMED of 101.8cumec and record length of 31 years and a percentage standard error of 6.47%. Therefore at the 67-percentile confidence interval = QMED*(1 ± 0.065).

The proposed flood growth factor which was derived by fitting the GLO distribution to the combined at-site and regionally pooled gauges. The statistical standard error of the flood Growth Factor X_T was determined using Monte Carlo simulation for a range of return periods.

Table 10-1 Statistical Error associated with Return Period Flood Estimates

Return Period T years	Growth Factor $X_T = Q_T/QMED$	Growth Factor XT Standard Error (%)	Flood Quantile QT Standard Error (%)
2	1.00	0.0	6.5
5	1.22	2.6	9.3
10	1.40	5.0	11.8
25	1.62	9.1	16.2
50	1.87	13.0	20.3
100	2.13	17.8	25.5
200	2.42	23.7	31.7
500	2.88	33.6	42.3
1000	3.30	43.1	52.4

The standard error of the flood quantile Q_T is expressed as follows:

$$se(Q_T) = \left(1 + se(QMED)\right)se(X_T)$$

At the upper confidence interval the Q100 will be 25.5 % higher and the Q1000 with be 52.4% higher. For Bellagill the Q100 and 67% upper confidence estimate is calculated as follows:

Q100 = QMED * 2.13 = 101.8 * 2.13 = 216.8 cumec
Q100(upper 67% CI) = Q100 *1.255 = 216.8 * 1.255 = 272.1cumec

Q1000 = 101.8 * 3.3 = 335.9cumec
Q1000(upper 67% CI) = 335.9 * 1.524 = 512 cumec

10.3 Model Error

A number of flood distribution types were examined and the best fit to the River Suck gauges was found to be produced from the use of a GLO distribution with the flood data presenting more like an S – curve type shape caused by the larger floods of 2009 and 2015, refer to Figure 5-5 to Figure 5-8 and Figure 5-21 to Figure 5-23. It should also be noted that both Athlone and Banagher AM series also display the same S-Curve type shape. This S-curve shape is not well represented by any statistical distribution type and for smaller samples can return more to an EV1 when the AM series size becomes bigger. This is unlikely to occur for the Suck gauges given that the sample period is reasonably long at typically 68years and also given that it is replicated at all four gauges, this behaviour appears more catchment response related to the bigger rainfall events. The use of the 3-parameter GLO distribution with an upward curving slope is considered the safer selection over the normally use EV1 distribution for Irish catchments and is more sympathetic to a jump in the AM data by the larger floods.

10.4 Measurement Error

The measurement error is associated with the flood rating curve that relates the recorded water level (Stage Height) to flow rate (Q). The critical gauge for this Study is Bellagill being the closest gauge located at the upstream boundary to the Ballinasloe study area and used as a single pivotal site for all the downstream HEP's along the River Suck mainline. The review of the Bellagill rating curve presented in Chapter 3 found that a reasonable flood range was available at this gauge with an HGF/ QMED ratio of 2.1. However, at the smaller floods where out of bank flows are occurring downstream of the gauge site a poor relationship was observed with a bigger scatter in the measured H-Q data. This was identified to be possibility due to the variability in overbank conveyance at the lower out of bank flood depths.

Taking into account the effect of the floodplain roughness variability through modelling and the degree of scatter in the H-Q measurement error and the potential hysteresis effect from the downstream flood plain the uncertainty in the flood rating relationship is likely to be of the order of ± 10%, which is within the acceptable range for flood flow estimation of an A1 station.

10.5 Trend in the AM series

The trend analysis presented in Section 7 has demonstrated that the AM series for Bellagill and the other associated gauges generally represent random samples but has identified a significant positive trend in flood magnitude with time at Bellagill and this trend is replicated by a number of the Shannon Gauges (i.e. Athlone and Banagher) and also, but to a lesser extent, at the upstream Derrycahill AM series.

Investigation of rainfall over longer durations associated with winter flooding on the Shannon and Suck Callows also suggest a positive increasing trend with time in the catchment rainfall depths.

The average annual increase in QMED based on the 2 Shannon and 4 Suck gauges over the full record of c. 68 to 70 year period (1950's to date) is 0.33% per annum. Of concern is the more dramatic increase in the QMED trend based on the recent decades with an average annual increase of 0.76% per annum for the period 1989 to date. Therefore, the use of QMED from the full population is likely to underestimate the current QMED value. No definite conclusion was reached with respect to a trend in the flood growth curve factors with time.

10.6 Recommended allowance for uncertainty in the estimated Flood Quantiles

The significant increasing trend in flood magnitudes with time as presented in Section 7 undermines the statistical principal of stationarity and homogeneity (i.e. being from a single parent population of flood events) which underpins the statistical frequency analysis. As a precautionary principal it is recommended to use a QMED of 101.8cumec, based the recent 3 decades for Bellagill in place of a QMED of 93.6cumec from the full record length. This represents an increase of 18.8% in the QMED and associated return period Q_T values for the Study. No changes to the recommended flood growth factors is proposed which were derived from the full record lengths of the pooling group stations.

The rating review estimates a potential ±10% standard error associated with the Bellagill flood rating relationship fit to the data. The flood frequency analysis quantified statistical sampling error (SE_T) associated with QT estimate of 6.5% at QMED, increasing to 25.5% at Q_{100} and 52.4% at Q_{1000}. Other uncertainties are associated with the catchment PCD data, the selected parent distribution, the potential increasing trend in flood magnitudes and timing and shape of the design flood hydrograph. These have been reduced through a review of the PCDs, selection of the best fit statistical model being a GLO and estimating the QMED based on the most recent 30years as opposed to the full record. Hydrograph timing and shape of tributary inflows will involve additional hydraulic sensitivity runs based initially on the dependance model results presented in Section 6 of this report.

It is recommended that the return period design flows include the statistical standard error representing the 67-percentile upper confidence interval. This approach of including the statistical error in the design flows is considered prudent given the uncertainty in the statistical analysis and potential future changes in the behaviour of floods. This practice is in keeping also with the OPW Section 50 hydrological design requirements for bridges and culverts which require the design flow to include as a minimum the addition of the statistical error. For the smaller ungauged catchments not using the Bellagill pivotal site the factorial standard error of the statistical estimation method (65% for the IH124 Equation and 37% for the FSU equation) are recommended in adjusting upwards the QMED.

For sensitivity analysis in respect to all other sources of error including rating measurement error it is recommended that a 10% factor is included in the sensitivity analysis of the hydraulic model predictions in respect to the design flow. The effect of future climate change of 20% and 30% increase in the flood peak magnitude at medium and high emission climate change scenarios should be examined in the hydraulic modelling.

11 Recommended Return Period Design Flood magnitudes

11.1 River Suck Recommended Return Period Design Flows – Current Scenario

Using the recommended flood growth curve for the study area presented in Table 5-18 the return period peak flood flow estimates are computed and presented in Table 11-1 below for the River Suck at Bellagill, Ballinasloe and River Shannon confluence. This design Floood Growth Curve is based on the Bellagill pivotal site with the QMED estimate from the most recent 3 decades of the AM flood series, giving a QMED of 101.8cumec and FSU pivotal adjustment factor of 1.101, refer to Section 7.5 and the inclusion of the estimated statistical error in the design flows, refer to Section 10.6.

Table 11-1 Recommended Design Flood Peak Flows for River Suck with statistical error included

Return Period T years	Growth Curve XT	Suck R. to Bellagill cumec	Suck R. to Marina Ballinasloe cumec	Suck R. to Shannon confluence cumec
2	1	108.4	137.9	153.7
5	1.22	135.5	172.6	192.3
10	1.4	159.4	202.7	225.9
25	1.62	191.6	243.8	271.7
50	1.87	228.7	291.5	324.7
100	2.13	272.1	346.0	385.7
200	2.42	324.1	412.9	460.0
500	2.88	416.8	530.7	591.3
1000	3.3	511.7	651.4	725.7

The 10, 100 and 1000year return period design flood flows to Bellagill are 159.4. 272.1 and 511.7cumec and to Ballinasloe Marina reach these increase to 202,7, 346.0 and 651.4cumec.

11.2 Recommended Return Period Design Flows in Tributaries – Current Scenario

In respect to the larger tributary rivers in excess of 25km^2, namely the Bunowen, Deerpark and Bellinure Rivers, the selected estimation method is the FSU QMED equation with Bellagill included at the pivotal site and multiplied by the recommended study GLO flood growth curve, refer to Section 5.5.

For the smaller tributaries, less than 25km^{2,} the IH124 equation with no pivotal site adjustment is recommended for QMED but with an adjustment for statistical factorial error of 1.65QMEDand also multiplied by the study GLO flood growth curve, refer to Section 5.6.

The return period peak flood flow estimates Q_T are presented in Table 11-2 for three larger tributary rivers and Table 11-3 for the smaller tributary streams.

Table 11-2 Recommended Design Flood Peak Flows in Tributary Rivers with the statistical error included

Return Period T years	Growth Curve XT	Bunowen R. to River Suck cumec	Deerpark R. to River Suck cumec	Bellinure R. to River Suck cumec
2	1.0	21.1	11.1	14.8
5	1.22	26.4	13.9	18.6
10	1.40	31.0	16.3	21.8
25	1.62	37.3	19.6	26.2
50	1.87	44.6	23.5	31.4
100	2.13	53.0	27.9	37.3
200	2.42	63.1	33.3	44.4
500	2.88	81.2	42.8	57.1
1000	3.30	99.6	52.5	70.1

Table 11-3 Recommended Design Flood Peak Flows in smaller tributary Streams without statistical error

Return Period T years	Growth Curve XT	Cuilleen S. to R. Suck cumec	Pollboy S. to R. Suck cumec	Loughbown to R. Suck cumec	Cuilliaghbeg to R. Suck cumec	Laurencetown to R. Suck cumec
2	1.0	2.25	0.59	1.60	1.77	3.40
5	1.22	2.74	0.72	1.95	2.16	4.15
10	1.40	3.15	0.83	2.24	2.47	4.76
25	1.62	3.64	0.96	2.59	2.86	5.51
50	1.87	4.21	1.10	2.99	3.30	6.36
100	2.13	4.79	1.26	3.41	3.76	7.24
200	2.42	5.44	1.43	3.87	4.28	8.23
500	2.88	6.48	1.70	4.61	5.09	9.79
1000	3.30	7.42	1.95	5.28	5.83	11.22

Table 11-4 Recommended Design Flood Peak Flows in smaller tributary Streams with statistical error included

Return Period T years	Growth Curve XT	Cuilleen S. to R. Suck cumec	Pollboy S. to R. Suck cumec	Loughbown to R. Suck cumec	Cuilliaghbeg to R. Suck cumec	Laurencetown to R. Suck cumec
2	1.0	3.71	0.97	2.64	2.92	5.61
5	1.22	4.65	1.22	3.30	3.66	7.02
10	1.40	5.46	1.43	3.88	4.29	8.25
25	1.62	6.56	1.72	4.67	5.16	9.92
50	1.87	7.84	2.06	5.58	6.17	11.85
100	2.13	9.32	2.44	6.62	7.33	14.08
200	2.42	11.11	2.91	7.90	8.74	16.79
500	2.88	14.28	3.75	10.16	11.24	21.59
1000	3.30	17.53	4.60	12.47	13.79	26.49

11.3 Flood Flow Estimates at HEPs

The QMED and Return Period Estimates QT for the current (present-day) scenario are presented in Table 11-5.

Table 11-5 Estimated Return Period Flood Flows at Primary HEPs within Ballinasloe Study

Watercourse	HEP ID	Q2	Q5	Q10	Q25	Q50	Q100	Q200	Q1000
trib_deerpark	26_2746_2	0.53	0.66	0.78	0.90	1.12	1.33	1.59	2.50
Deerpark	26_682_5	10.7	13.3	15.7	18.0	22.5	26.8	31.9	50.4
Deerpark	26_682_6	10.7	13.4	15.7	18.1	22.6	26.9	32.0	50.6
Deerpark	26_682_7	10.8	13.4	15.8	18.2	22.7	27.0	32.2	50.8
Cuilleen	26_936_2	4.1	5.1	6.0	6.9	8.6	10.2	12.2	19.2
Cuilleen	26_936_3	4.1	5.1	6.0	7.0	8.7	10.3	12.3	19.4
Suck	26_1397_1	108.5	135.7	159.5	183.4	229.0	272.4	324.5	512.3
Suck	26_1397_2	109.0	136.3	160.3	184.3	230.1	273.7	326.1	514.7
Suck	26_1397_3	109.1	136.3	160.3	184.3	230.1	273.7	326.1	514.7
Suck	26_1419_4	108.5	135.7	159.5	183.4	229.0	272.4	324.5	512.3
Bunowen R.	26_2853_5	20.3	25.4	29.9	34.3	42.9	51.0	60.7	95.9
Bunowen R.	26_3041_1	20.6	25.8	30.3	34.8	43.5	51.7	61.6	97.2
Bunowen R.	26_3041_2	21.0	26.3	30.9	35.5	44.3	52.7	62.8	99.2
Bunowen R.	26_3041_3	21.1	26.3	30.9	35.6	44.4	52.8	63.0	99.4
Bunowen R.	26_3041_4	21.1	26.4	31.0	35.7	44.5	53.0	63.1	99.6
Bunowen R.	26_3041_5	21.1	26.4	31.0	35.7	44.5	53.0	63.1	99.6
Deerpark	26_3977_1	10.8	13.5	15.9	18.2	22.8	27.1	32.3	50.9
Deerpark	26_3977_2	10.8	13.4	15.8	18.2	22.7	27.0	32.2	50.8
Deerpark	26_3977_3	11.1	13.9	16.3	18.8	23.4	27.9	33.2	52.4
Deerpark	26_3977_4	11.2	14.0	16.4	18.9	23.6	28.1	33.5	52.8
Deerpark	26_3977_5	11.1	13.9	16.3	18.8	23.5	27.9	33.3	52.5
Loughbown	26_3824_9	2.88	3.60	4.24	4.87	6.08	7.23	8.62	13.60
Loughbown	26_3824_10	3.00	3.75	4.41	5.07	6.33	7.53	8.97	14.16
Pollboy26	26_3033_1	0.85	1.06	1.24	1.43	1.78	2.12	2.53	3.99
Pollboy26	26_3033_2	0.95	1.19	1.40	1.61	2.01	2.40	2.85	4.51
Pollboy26	26_3033_3	1.03	1.29	1.52	1.75	2.18	2.59	3.09	4.87
Pollboy26	26_3033_4	1.13	1.41	1.65	1.90	2.37	2.82	3.36	5.31
Pollboy26	26_3033_5	1.13	1.41	1.66	1.91	2.38	2.83	3.37	5.33

Watercourse	HEP ID	Q2	Q5	Q10	Q25	Q50	Q100	Q200	Q1000
Suck	26_1442_1	111.1	138.9	163.3	187.7	234.4	278.8	332.2	524.3
Suck	26_1442_2	111.1	138.9	163.3	187.8	234.4	278.9	332.2	524.4
Suck	26_1442_3	111.1	138.9	163.3	187.8	234.4	278.9	332.2	524.4
Suck	26_1442_4	111.1	138.9	163.3	187.8	234.4	278.9	332.2	524.4
Suck	26_3976_1	131.7	164.7	193.7	222.6	278.0	330.7	393.9	621.8
Suck	26_3976_2	132.0	164.9	194.0	223.0	278.4	331.2	394.6	622.8
Suck	26_3976_3	132.0	165.0	194.1	223.1	278.6	331.4	394.8	623.2
Suck	26_3976_4	132.1	165.2	194.2	223.3	278.8	331.7	395.1	623.7
Suck	26_3976_5	132.1	165.2	194.2	223.3	278.8	331.7	395.1	623.7
Suck	26_3978_2	138.9	173.6	204.2	234.7	293.0	348.6	415.3	655.5
Suck	26_3978_3	138.4	173.0	203.4	233.8	292.0	347.3	413.7	653.1
Suck	26_3978_4	138.4	173.0	203.5	233.9	292.1	347.4	413.9	653.3
Suck	26_3978_5	138.5	173.1	203.6	234.0	292.2	347.6	414.1	653.6
Suck	26_3978_6	138.6	173.2	203.7	234.2	292.4	347.8	414.3	654.0
Suck	26_3978_7	138.6	173.2	203.7	234.2	292.4	347.9	414.4	654.1
Suck	26_1414_1	138.6	173.3	203.7	234.2	292.4	347.9	414.4	654.2
Suck	26_1414_2	138.5	173.2	203.6	234.1	292.3	347.7	414.2	653.9
Suck	26_1414_3	138.6	173.3	203.8	234.3	292.5	347.9	414.5	654.3
Suck	26_1414_4	138.6	173.2	203.7	234.2	292.4	347.9	414.4	654.2
Suck	26_1415_1	138.8	173.5	204.1	234.6	292.9	348.5	415.1	655.3
Suck	26_1415_2	138.9	173.6	204.1	234.7	293.0	348.5	415.2	655.4
Suck	26_1436_2	138.9	173.7	204.2	234.8	293.2	348.7	415.4	655.8
Suck	26_1436_3	139.7	174.6	205.3	236.0	294.7	350.6	417.6	659.2
Suck	26_1436_4	140.1	175.1	205.9	236.7	295.5	351.5	418.8	661.1
Suck	26_3831_2	141.2	176.4	207.5	238.6	297.8	354.3	422.1	666.3
Suck Bellagill	26_1419_1.5	108.4	135.5	159.4	183.2	228.7	272.1	324.1	511.7
Suck Derrycahill	26_1402_1.5	97.8	122.3	143.8	165.3	206.4	245.5	292.5	461.7

12 Summary and Conclusions

A detailed hydrological assessment of the River Suck and its tributaries at Ballinasloe was undertaken as part of the Ballinasloe Flood Relief Scheme. The objective is to provide reliable estimates of return period flood magnitudes and hydrographs for input to the hydraulic flood model and ultimately the design of the flood relief measures that the Flood Relief Scheme will comprise of. The hydrological assessment involved collating and reviewing relevant topographical, meteorological and hydrometric data sets, reviewing historical flooding at Ballinasloe, carrying out statistical flood frequency analysis, trend analysis and likely future catchment changes and uncertainty analysis.

A rating review of the relevant hydrometric gauges concluded that a slight adjustment to the Bellagill flood flow rating relationship was warranted. The new rating reduced the larger flood flow estimates by c. 5%, for example, the historical maximum flood magnitude associated with the November 2009 event reduced from an estimate of 224cumec to 212.5cumec and the lower return period flood flows increased slightly, with the 2-year QMED estimate increasing from 89cumec to 93.6cumec.

The design flood flows and hydrographs for a range of return periods 2, 5, 10, 20, 50, 100, 200 and 1000years were estimated using the FSU PCD method for all catchments greater than 25km^2 and using the Bellagill gauged site as the pivotal adjustment factor in the QMED estimate. For the smaller catchments, less than 25km^2 the IH124 flood estimation method was used.

A single flood growth curve is recommended for all tributary stream and rivers and the mainline River Suck. This flood growth curve was developed using a 3parameter GLO statistical distribution and combined a regional based pooling group of Suck hydrometric gauges with 40% weighting to the at-site Bellagill station and 20% weighting to each of other three gauge sites within the pooling group, namely Derrycahill, Rockwood and Willsbrook.

The design flood hydrograph analysis recommends fitting a hydrograph shape based on the average shape profile derived from the 2009 and 2015 extreme flood hydrographs that were recorded at the Bellagill gauge. A modified FSR triangular hydrograph method is to be used on the Tributary streams and rivers. Further sensitivity testing is required during hydraulic modelling in terms of fine tuning the tributary inflow hydrographs in respect to flood peak magnitude, flood volume and timing. The suck catchment area only increases by 18 % from Bellagill to Ballinasloe, and consequently, the influence of the tributary inflows, namely the Bunowen (137km^2) and Deerpark(62km^2) on resultant hydrograph shape and flooding in the River Suck at Ballinasloe is not significant.

Statistical trend analysis concluded that there is a significant positive trend with time in increasing flood magnitudes and frequency over the recorded period of almost 70years which is associated to increased rainfall magnitudes as opposed to catchment changes. This trend significantly increased from the 1990's onwards with QMED increasing by 0.76 % per annum. Taking a precautionary approach in regard to the increasing trend in QMED, the QMED estimate at the Bellagill gauged site, used as a pivotal adjustment site the ungauged HEPs, is based on the period from 1989 onwards (the most recent 3 decades) as opposed to the entire 68year record.

No definite trend was identified in the growth curve and given the requirement for a long record, the design flood growth curve is based on the available full record length at all of the pooled stations.

It is recommended that the climate change allowances of 20% and 30% increase at the Mid-Range Future Scenario (MRFS) and the High-End Future Scenario (HEFS) be included for both storm rainfall and flood runoff in assessing the adaptation of the proposed Flood relief scheme to future change.

Future potential catchment land-use changes, agriculture and forestry, are not considered in the case of the Large River Suck catchment and its tributaries the Deerpark and Bunowen as significant drivers for the increase in the design flood magnitudes and hydrograph shape through Ballinasloe. The potential impact of local urbanisation within or contributing to flows within potential defended lands will require careful consideration, particularly where temporary storage or pumping of storm flows from the defended areas will be required.

The uncertainty analysis estimates a potential ±10% measurement error associated with the Bellagill flood rating relationship. The flood frequency analysis quantified statistical sampling error (SE_T) associated with Q_T estimate of 6.5% at QMED, increasing to 25.5% at Q_{100} and 52.4% at Q_{1000}. Other uncertainties are associated with the catchment PCD data, the selected parent distribution, the potential increasing trend in flood magnitudes and timing and shape of the design flood hydrograph. These have been reduced through a review of the PCDs, selection of the best fit statistical model being a GLO and estimating the QMED based on the most recent 30years as opposed to the full record. Hydrograph timing and shape of tributary inflows will involve additional hydraulic sensitivity runs based initially on the dependance model results presented in Section 6 of this report.

It is recommended that the return period design flows include the statistical standard error representing the 67-percentile upper confidence interval. This approach of including the statistical error in the design flows is considered prudent given the uncertainty in the statistical analysis and potential future changes in the behaviour of floods. This practice is in keeping also with the OPW Section 50 hydrological design requirements for bridges and culverts which require the design flow to include as a minimum the statistical error. For the smaller ungauged catchments not using the Bellagill pivotal site the factorial standard error of the statistical estimation method (65% for the IH124 Equation and 37% for the FSU equation) are recommended for adjusting upwards QMED.

For sensitivity analysis in respect to all other sources of error including rating measurement error it is recommended that a 10% factor is included in the sensitivity analysis of the hydraulic model predictions in respect to the design flow. The effect of future climate change of 20% and 30% increase in the flood peak magnitude at medium and high emission climate change scenarios should be examined in the hydraulic modelling.

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